

AD-A009 335

SIGNAL ENHANCEMENT OF LPE DATA

Duane D. Nelson, et al

Teledyne Geotech

Prepared for:

Defense Advanced Research Projects Agency

27 August 1973

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER SDAC-TR-73-4	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER <i>AD-A009 335</i>
4. TITLE (and Subtitle) SIGNAL ENHANCEMENT OF LPE DATA		5. TYPE OF REPORT & PERIOD COVERED Technical
7. AUTHOR(s) Nelson, Duane D. von Seggern, David H.		6. PERFORMING ORG. REPORT NUMBER
9. PERFORMING ORGANIZATION NAME AND ADDRESS Teledyne Geotech 314 Montgomery Street Alexandria, Virginia 22314		8. CONTRACT OR GRANT NUMBER(s) F08606-74-C-0006
11. CONTROLLING OFFICE NAME AND ADDRESS Defense Advanced Research Projects Agency Nuclear Monitoring Research Office 1400 Wilson Blvd.-Arlington, Virginia		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office) Vela Seismological Center 312 Montgomery Street Alexandria, Virginia 22314		12. REPORT DATE 27 August 1973
		13. NUMBER OF PAGES <i>149</i>
		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION DOWNGRADING SCHEDULE
16. DISTRIBUTION STATEMENT (of this Report) APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED.		
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)		
18. SUPPLEMENTARY NOTES		
19. KEY WORDS (Continue on reverse side if necessary and identify by block number) Match Filter Non-linear Filter Rayleigh-wave Enhancement Long-Period Experimental Network		
20. ABSTRACT (Continue on reverse side if necessary and identify by block number) In this report we investigate signal/noise ratio enhancement obtainable on single-station LPE recordings by several techniques. The processors which are compared over a data base of 20 events include simple band-pass filtering, match filtering with a synthetic LR signature, and time-varying non-linear processing which examines three-component data for Rayleigh-wave characteristics. For the suite of events in this study, average S/N ratio		

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SECURITY CLASSIFICATION OF THIS PAGE(When Data Entered)

SIGNAL ENHANCEMENT OF LPE DATA

Seismic Data Analysis Center Report No.: SDAC-TR-73-4

AFTAC Project No.: VELA VT/4709
Project Title: Seismic Data Analysis Center
ARPA Order No.: 1620
ARPA Program Code No.: 3F10

Name of Contractor: TELEDYNE GEOTECH

Contract No.: F08606-74-C-0006

Date of Contract: 01 July 1973

Amount of Contract: \$2,152,172

Contract Expiration Date: 30 June 1974

Project Manager: Robert G. Van Nostrand
(703) 836-3882

P. O. Box 334, Alexandria, Virginia 22314

APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED.

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ABSTRACT

In this report we investigate signal/noise ratio enhancement obtainable on single-station LPE recordings by several techniques. The processors which are compared over a data base of 20 events include simple band-pass filtering, match filtering with a synthetic LR signature, and time-varying non-linear processing which examines three-component data for Rayleigh-wave characteristics. For the suite of events in this study, average S/N ratio improvement is 6 db for match filtering, 15 db for the non-linear PHILTRE processor and 20 db cascading the two processors.

TABLE OF CONTENTS

	Page No.
ABSTRACT	
INTRODUCTION	1
METHODS	2
DATA	7
RESULTS	8
CONCLUSIONS	12
SUGGESTIONS FOR FURTHER STUDIES	13
REFERENCES	14

LIST OF FIGURES

Figure No.	Figure Title	Page No.
1	CTA - Site and Event Locations	16
2	KIP - Site and Event Locations	17
3	KON - Site and Event Locations	18
4	Processing Results for CTA-1	19
5	Processing Results for CTA-2	20
6	Processing Results for CTA-3	21
7	Processing Results for CTA-4	22
8	Processing Results for CTA-5	23
9	Processing Results for CTA-6	24
10	Processing Results for KIP-1	25
11	Processing Results for KIP-2	26
12	Processing Results for KIP-3	27
13	Processing Results for KIP-4	28
14	Processing Results for KIP-5	29
15	Processing Results for KIP-6	30
16	Processing Results for KIP-7	31
17	Processing Results for KIP-8	32
18	Processing Results for KIP-9	33
19	Processing Results for KIP-10	34
20	Processing Results for KON-1	35
21	Processing Results for KON-2	36
22	Processing Results for KON-3	37
23	Processing Results for KON-4	38
24	Histograms of signal enhancement by each of the four processors on 25 events	39
25	Distribution of raw signal/noise ratios	40

INTRODUCTION

Recent work at the Seismic Data Laboratory has shown that the network of Long Period Experimental (LPE) stations has a 90% threshold of approximately 4.7 (m_b) for detection of surface waves from global events (Von Seggern, 1973). This is not nearly low enough to insure detection of surface waves from many events of interest, especially underground nuclear explosions of low yield. Since these stations record data in digital form, it is relatively easy to attempt to improve this threshold by digital processing. Many signal-enhancement processing experiments have been reported for other long-period seismic systems (e.g., Capon et al.; 1969; Binder, 1970; Simons, 1968); but because of the quite different response of LPE systems (compared, for instance, to WWNSS or LRSM long-period responses) we feel that a thorough experiment with available processing methods is warranted. In this report we examine and compare the signal enhancement effected on a suite of events by the following methods: band-pass filtering, match filtering, and non-linear time-varying processing.

METHODS

Band-pass Filtering

As a reference point for judging the effectiveness of our more sophisticated signal enhancement methods, a narrow band-pass filter was also applied to the LPE data. We employed a program (LOPAZ) which simulates analog filtering of digital data. The corner frequencies were set to .025 and .040 Hz (25 to 40 seconds period) with 24 db rolloff on each side. This filter should produce an output which will be free of any microseismic noise and which will take maximum advantage of the minimum in earth noise at 30 to 40 seconds period (Savino et al., 1972).

Match Filtering

This is a signal enhancement technique whereby one crosscorrelates a time window containing the desired signal with a reference waveform having presumably a nearly identical character. Three different approaches are commonly used in constructing this reference waveform. One is an empirical approach which uses a seismic signature with large S/N ratio from the same region as the signal to be match-filtered (Alexander and Rabenstine, 1967; von Seggern, 1971). A second approach is to construct a swept-frequency or chirp waveform from an analytic formula (Capon et al., 1969). A third is to synthesize the reference waveform from known or estimated surface-wave velocities (Alexander

and Rabenstine, 1967)); this is usually done by inverse transforming frequency-domain data points defined by the phase velocities at each Fourier frequency.

For this study a variation of the third approach was employed. Subroutine SURFIL (Kimball and Johnson, 1970) synthesized the reference waveform in the time domain point by point. It uses group velocity information provided for periods between 50 and 10 seconds by subroutine SURTT (Massé and Crowley, 1968; and Kimball, 1969). This in global grid form, each grid area being assigned one of sixteen possible Rayleigh-wave, group velocity, dispersion curves; SURTT defines the great circle path between the epicenter and station and then averages the slownesses at each period over the multiple grid areas traversed. The envelope of the waveform constructed by SURFIL is shaped by the instrument amplitude responses; however, attenuation was not taken into account in constructing the waveform. Adding the attenuation would not significantly affect results since the attenuation factor over the 20 to 50 seconds band is not highly variable (Tryggvason, 1965) and the precision of the amplitude spectrum is not as nearly as important for match filtering as that of the phase spectrum (Alexander and Rabenstine, 1967). For uniformity a length of 450 seconds was always used with this synthetic reference waveform.

The program MATCH (Johnson, 1970) which calls these subroutines has within it a band-pass filter which windows the frequency-domain amplitudes of the transformed time

trace. Its corner frequencies are .0165 and .067 Hz; the falloff is linear to zero amplitude at .01 and .10 Hz, respectively. This gives an effective bandpass for periods between approximately 12 and 80 seconds. This band-pass filter was used in all the match-filter processing presented in this report. This is not an effective filter, however, for most of the LPE recordings used here, since the LPE response allows little noise energy outside this band to appear on the recordings anyway, and so the filter's contribution to S/N ratio enhancement in the match-filter results is probably small (2 or 3 db).

Non-linear Time-varying Filtering

Time-varying adaptive filters using three-component recordings have been used previously for seismic signal enhancement. Sax and Mims (1965) discussed the use of polarization filters to enhance short-period data. Choy and McCamy (1973) used a polarization filter on LPE data recorded at OGD to inspect the relative phase angle between vertical and horizontal motion in order to enhance Rayleigh waves. They also used separately an azimuth discriminator to enhance Love waves.

For this study the time-varying processor used is the program PHILTRE developed by Simons (1968). This program operates on all three traces after rotating the horizontal traces to be radial and transverse to the great-circle path from epicenter to stations. It is thus dependent on at least crude epicenter locations

for the event being processed and also on good operation and calibration of all three instruments. After the traces are transformed to the frequency domain, PHILTRE applies three criteria to pass the Rayleigh-wave signal of interest and attenuate all else. First, the frequency components are weighted according to the deviation of the direction of approach of the energy, as given by the relative amplitudes of the rotated horizontal traces. Second, the frequency components are weighted according to whether they have the expected 90° phase lag between vertical and radial traces. Third, they are weighted according to whether they have the expected ellipticity for LR motion (values of 0.6 to 1.0 for the frequencies of interest). A full explanation of the scheme can be found in Simons (1968). We used weighting exponents of 8, 4, and 0 for the azimuth, phase lag, and ellipticity criteria, respectively. (The ellipticity criterion was suppressed since it is frequency and station epicenter dependent, and we did not have specific information on it.) The weighted harmonic components are inverse transformed for each trace to produce the output. Using data sampled at 0.5 pts/sec to speed up processing time, 256-second time windows are transformed to the frequency domain. These time windows are successively stepped down the record $1/8$ of the window length (32 seconds) to produce overlapping outputs which are then averaged to produce a single continuous output for each component. The same broadband prefilter as used in the match filtering is used

in the PHILTRE processing. Although gains are equalized between the three components for computing purposes, they are not equalized on the plots comprising the top six traces of Figures 4 through 23.

A Cascaded Processor

As a final processor we match-filtered the output from PHILTRE: that is, crosscorrelated the PHILTRE vertical output with the synthetic waveform used previously on the raw vertical trace.

DATA

For this study the receivers are at three of the LPE sites: CTA (Charters Towers, Australis), KIP (Kipapa, Hawaii) and KON (Kongsberg, Norway). Twenty events varying from m_b 3.7 to 5.5 (mean = 4.61) were randomly chosen with epicentral distances varying from 33° to 137° . Figures 1 through 3 show location of these stations and their associated events; and coordinates and magnitude of the events are included in Table I. Epicenters are from the NOS List with the exception of 3 from the LASA daily bulletin. Most of the Rayleigh waves in this data base are near the visual detection threshold; we in fact know that two (KIP-8, KIP-10) were undetected in routine analysis of the LPE data at the SDL.

The frequency response of the LPE system is centered at approximately 40 seconds period to minimize background noise and hopefully to improve detection of earthquake Rayleigh waves (Savino et al., 1972). Seismic data are digitally recorded at the sites with a sampling interval of one second.

Table 1.
LPE Event Parameters and Processor Results

EVENT	AREA	EPICENTER DATA		m _b	Δ	STATION DATA		PROCESSING GAINS (db)			
		ORIGIN*	COORD			θ	S/N _{in}	LOPAZ	MATCH	PHILTRE	P+M
CTA 1	Carlsburg Ridge	04-102458	01S 67E	4.9	79	273	35	2.2	4.6	19.6	19.6
CTA 2	S. of Mariana Is.	05-143216	13N144E	4.8	33	356	8	3.5	6.4	11.4	16.9
CTA 3	Tonga Is.	06-195557	16S173W	4.8	39	91	11	4.1	6.4	12.4	14.6
CTA 4	Off Coast of Peru	08-030237	11S 79W	5.0	126	120	9	4.6	5.1	5.2	3.0
CTA 5	Peru	08-133428	10S 75W	4.9	129	122	7	4.6	6.4	22.6	26.8
CTA 6	Near Coast of Chile	09-131212	30S 72W	4.9	118	143	6	2.3	7.2	18.5	12.4
KIP 1	Andreanoff Is.	02-214647	52N175W	4.9	33	341	58	5.6	7.6	30.6	37.4
KIP 2	S. E. Indian Rise	03-053712	42S 88E	4.9	133	232	19	0.8	5.6	9.6	15.4
KIP 3	N. Atlantic Ridge	03-105340	20N 46W	4.9	102	62	11	4.1	5.6	14.2	27.8
KIP 4	Tonga Is.	04-221237	15S173W	5.5	40	203	104	2.5	4.0	8.0	14.6
KIP 5	E. Coast Kamchatka	06-104332	56N163W	4.7	45	330	20	4.8	6.8	27.2	31.4
KIP 6	N. Atlantic Ridge	06-120743	34N 46W ^L	3.9	96	49	7	5.1	10.1	16.4	22.8
KIP 7	N. Atlantic Ridge	06-142222 ^L	33N 39W	4.8	100	48	9	4.6	12.9	16.1	22.8
KIP 8	W. Greenland	07-091945 ^L	62N 47W ^L	3.9	83	26	7	3.7	0.2	6.0	6.8
KIP 9	Gulf of Alaska	10-223546 ^L	59N150W	4.3	38	006	5	3.7	9.0	16.0	18.6
KIP 10	S. Yukon Territory	11-011158	62N140W	3.7	42	012	6	6.8	10.1	22.3	25.8
KON 1	Aleutian Is.	01-030825	51N170W	5.0	70	359	56	2.0	-1.1	9.8	9.2
KON 2	N. Atlantic	04-051140	58N 34W	4.5	22	282	29	6.0	3.5	7.6	16.6
KON 3	Sawu Sea	04-140048 ^L	24S180W	4.5	145	3	5	7.2	6.8	21.8	34.3
KON 4	E. Coast Kamchatka	05-041253	56N163E ^L	4.3	62	16	7	5.6	6.4	14.2	15.8
MEAN								4.2	6.2	15.3	19.6

* Day and time in June 1972

Δ = distance (degrees)

θ = back azimuth

S/N = raw signal (pp)/raw noise (rms)

L = LASA daily bulletin epicenter

RESULTS

Figures 4 through 23 are 30-minute plots for each of the 20 events. Each figure shows 11 traces: traces 1-3 are the vertical, radial and transverse broad-band filtered input to PHILTRE, traces 4-6 are PHILTRE output, trace 7 is the synthetic LR, trace 8 is the cross-correlation of traces 1 and 7, trace 10 is the narrow-band filter output, and trace 11 is the raw vertical component shown as a reference. Table I lists the S/N improvement in db of the various processors. Figure 24 shows histograms of the enhancement distribution over the 20 events using increments of 3 db. S/N ratio is defined in this report as a visual measurement of the maximum peak-to-peak signal amplitude, divided by the rms noise amplitude computed from a 256-second window. The noise window is the first 256 seconds on the plots; its position is held invariant for each input or output trace for that event.

Although for the most part we let the tabulated values and illustrated traces speak for themselves, a few results deserve comment. The mean processor gain is 4 to 5 db for the tight band-pass filter, 6 to 7 db for match filtering, 15 to 16 db for PHILTRE, and 19 to 20 db for PHILTRE + MATCH. Choy and McCamy (1973) have reported to a 6 db average gain over a unspecified number of cases when they used a Rayleigh-wave enhancer operating on phase angle only. Our PHILTRE results are

much better, perhaps reflecting the superiority of Simons' processor and the fact that we have included in the PHILTRE results that improvement obtained by band-passing the data with a broad-band filter. Table I lists three events for which the improvement of the cascaded processor is less than for PHILTRE alone and four events where the cascaded processor does better than the sum of the two individual processor results. These results are not so surprising when we consider we are really trying to relate results of MATCH on PHILTRE output to results of MATCH on raw data, the discrepancies arising from the time-varying aspects of the non-linear PHILTRE processor.

Another observation is that events which are greatly enhanced by one processor were seldom so greatly enhanced by another. For example, the events match filtering did best on had only average S/N enhancement in PHILTRE, while most of the events with high S/N improvement in PHILTRE (over 20 db) showed little match-filter improvement over that of the tight band-pass filter. One is led to suspect that this is due to the differing characteristics of the processors. Match filtering assumes that all group velocity grid values are fairly well known and neglects multipath effects (Binder, 1970). PHILTRE is unaffected by multipathing from back azimuths near the great circle azimuths, but is hampered by extraneous coherent energy approaching from the same azimuth as the signal to be enhanced.

Considering enhancement as a function of travel path, the majority of PHILTRE gains over 20 db are attributable to circum-Pacific events arriving at KIP while those with high S/N improvement in match filtering include only some of these, and two from the North Atlantic to KIP across the United States. Events with poorer than average S/N improvement on both PHILTRE and MATCH include events whose travel paths were from Peru to CTA, Greenland to KIP, and the North Atlantic to KON.

It is important to know whether a processor will do as well on weak signals as on strong signals. To check this, the processors' S/N improvement populations were divided into "high-gainer" and "low-gainer" classes to see if such a division correlates with input S/N ratio. The histograms of S/N ratios of the raw data shown in Figure 25 demonstrates that there are at least as many "high-gainers" among the weak signals as among the strong signals (in fact both MATCH and PHILTRE appear to do better on weak signals for this population). For comparison, a visual detection threshold of 1:1 (S_{pp}/N_{pp}) is shown relative to the event distributions. We do not have signals well below this threshold and therefore cannot determine how rapidly the processors degrade with low S/N ratios.

CONCLUSIONS

Over our suite of 20 events, match filtering improved S/N ratio by 6 to 7 db. This figure is roughly what is expected (Capon et al., 1969); and its 2 db improvement over band-pass filtering alone on these events is also roughly what has been achieved before (Binder, 1970). Although match filtering shows some 2 db advantage over band-pass filtering here, PHILTRE shows a very significant 11 db advantage over it.

The combination of PHILTRE + MATCH achieved on the average a remarkable S/N ratio improvement of 20 db over raw traces (this includes the wide band-pass prefilter as described above). We can comfortably predict, though, that this 20 db cannot hold up for signals below the visual threshold. The PHILTRE processor depends upon finding some signal component with which to reject the noise; and when noise begins to dominate, the processor may never find the signal component. The calculations required by PHILTRE + MATCH are not cumbersome, and real-time implementation would be easily attainable. However, disadvantages of these processors are that application of PHILTRE requires all three components and knowledge of back azimuths to events being processed and that application of MATCH requires at least crude estimates of the epicenter locations of events being processed. These event location parameters should be readily obtainable from short-period network detections though.

SUGGESTIONS FOR FURTHER STUDIES

Three further studies are suggested by the results of this report: one would be a comparison of signal-to-noise ratio obtainable for an LPE site versus an array, using, for instance, KON and NORSAR data for common events. The cascaded PHILTRE-MATCH processor would operate on the KON data while the NORSAR data would first be beamformed before the same cascaded processor was applied to it. A second study would use the cascaded processor to see how far the detection threshold of an LPE station can be lowered by processing the data at predicted Rayleigh-wave arrival times for visually undetected events of a given low m_b for a specific region. A third study would be to evaluate what capability PHILTRE has to separate mixed events recorded by a single three-component site due to its azimuthal discrimination and phase isolation characteristics.

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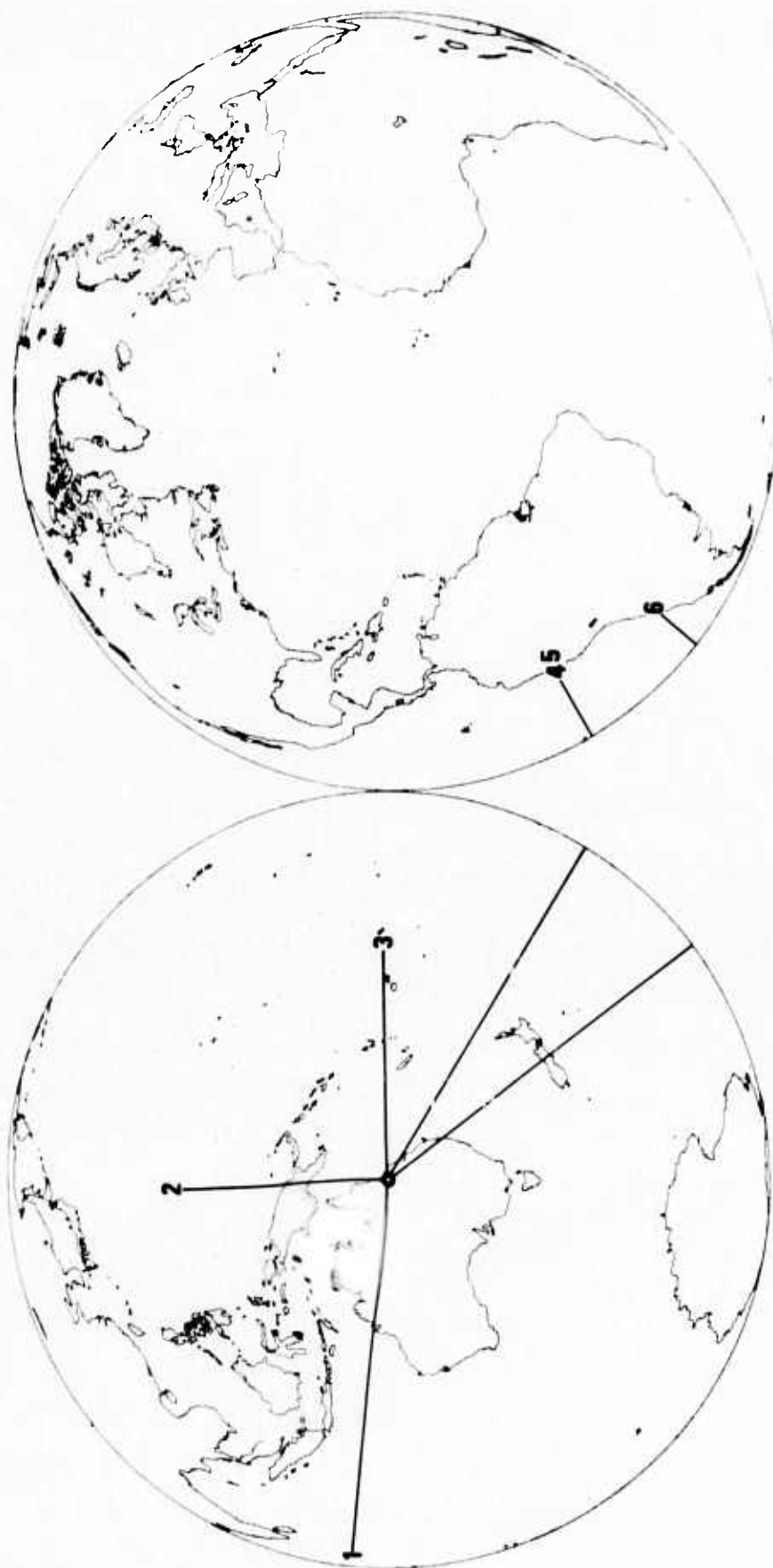


Figure 1. CTA - Site and Event Locations

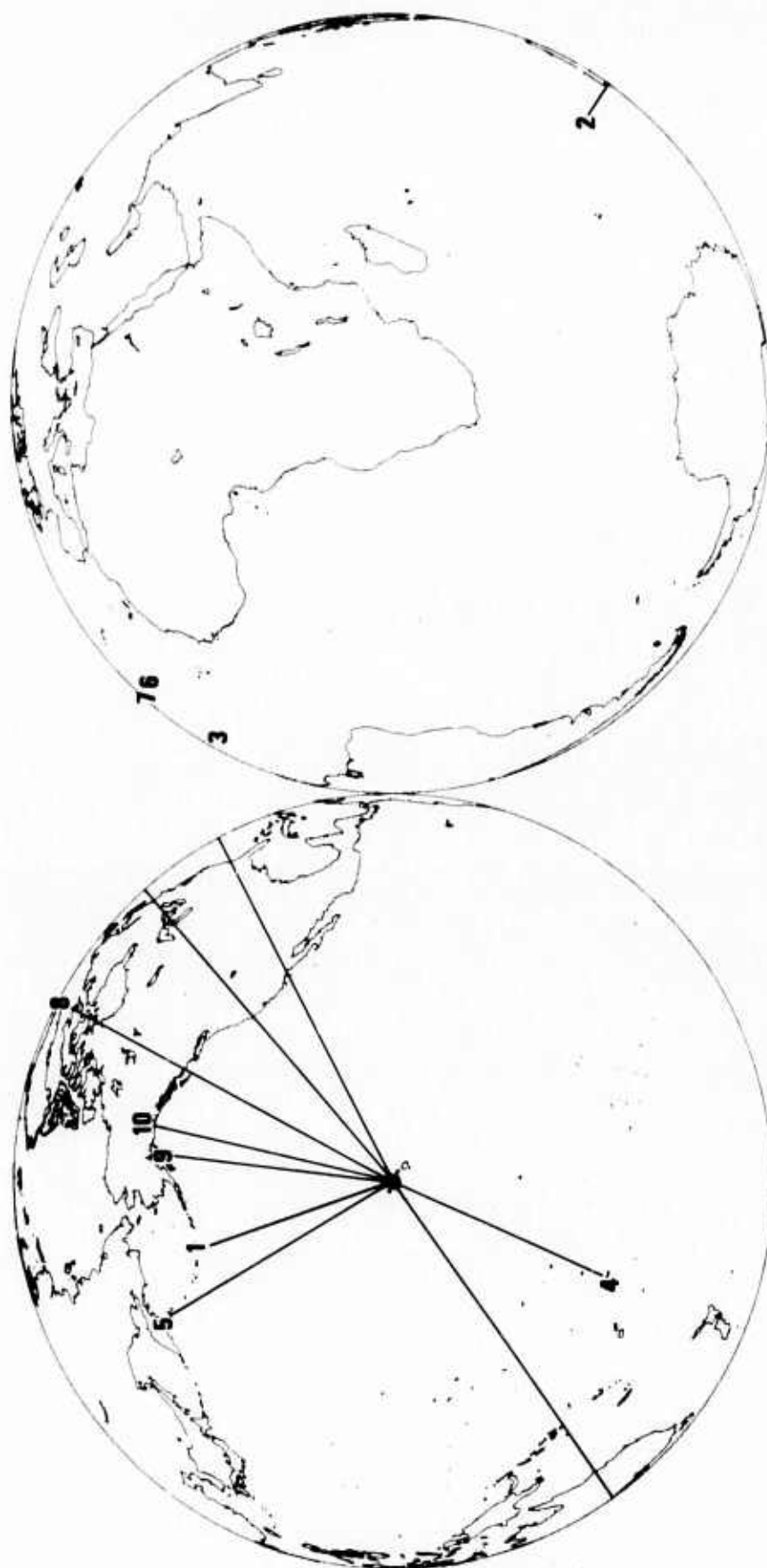


Figure 2. KIP - Site and Event Locations

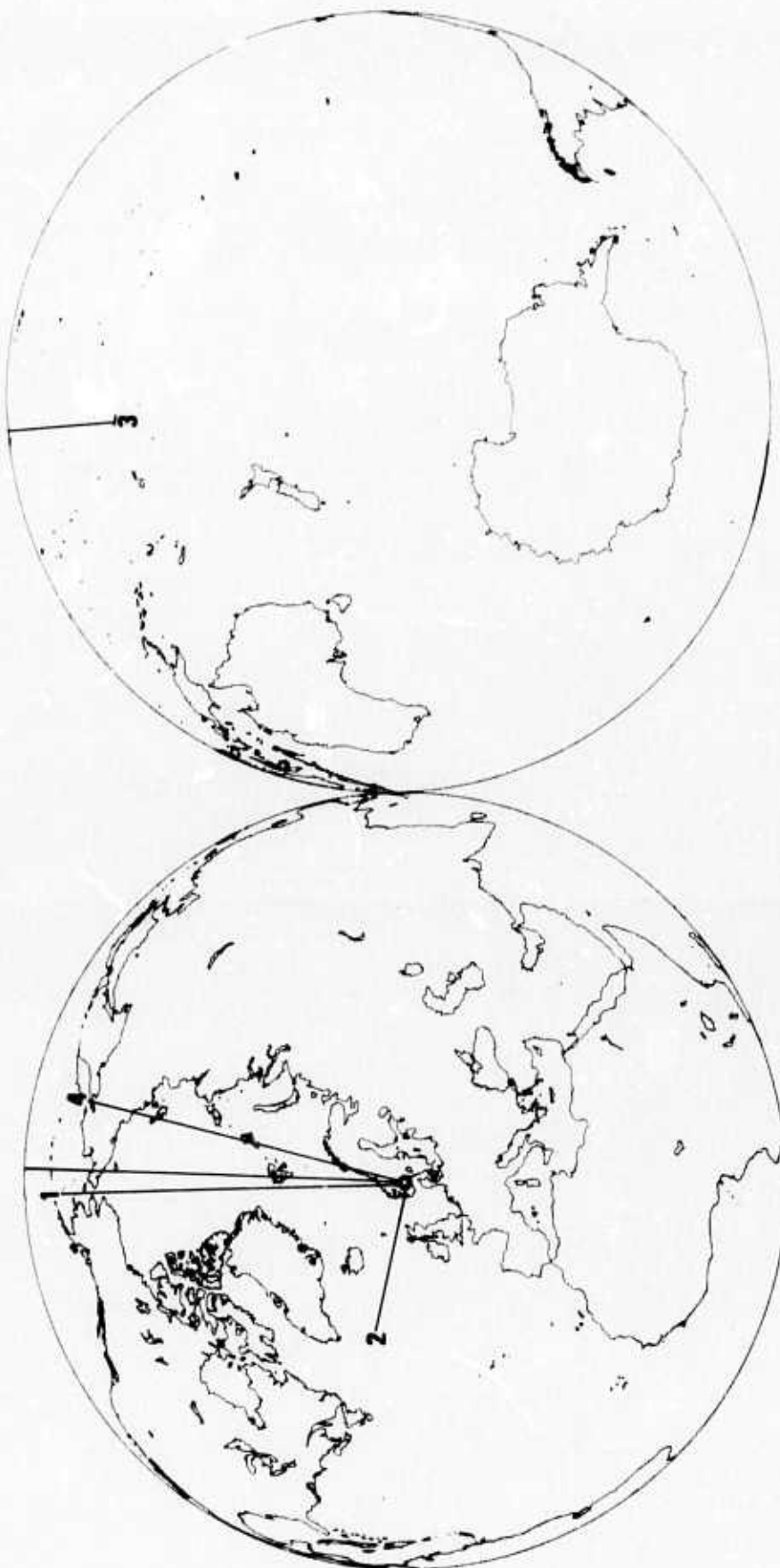


Figure 3. KON - Site and Event Locations

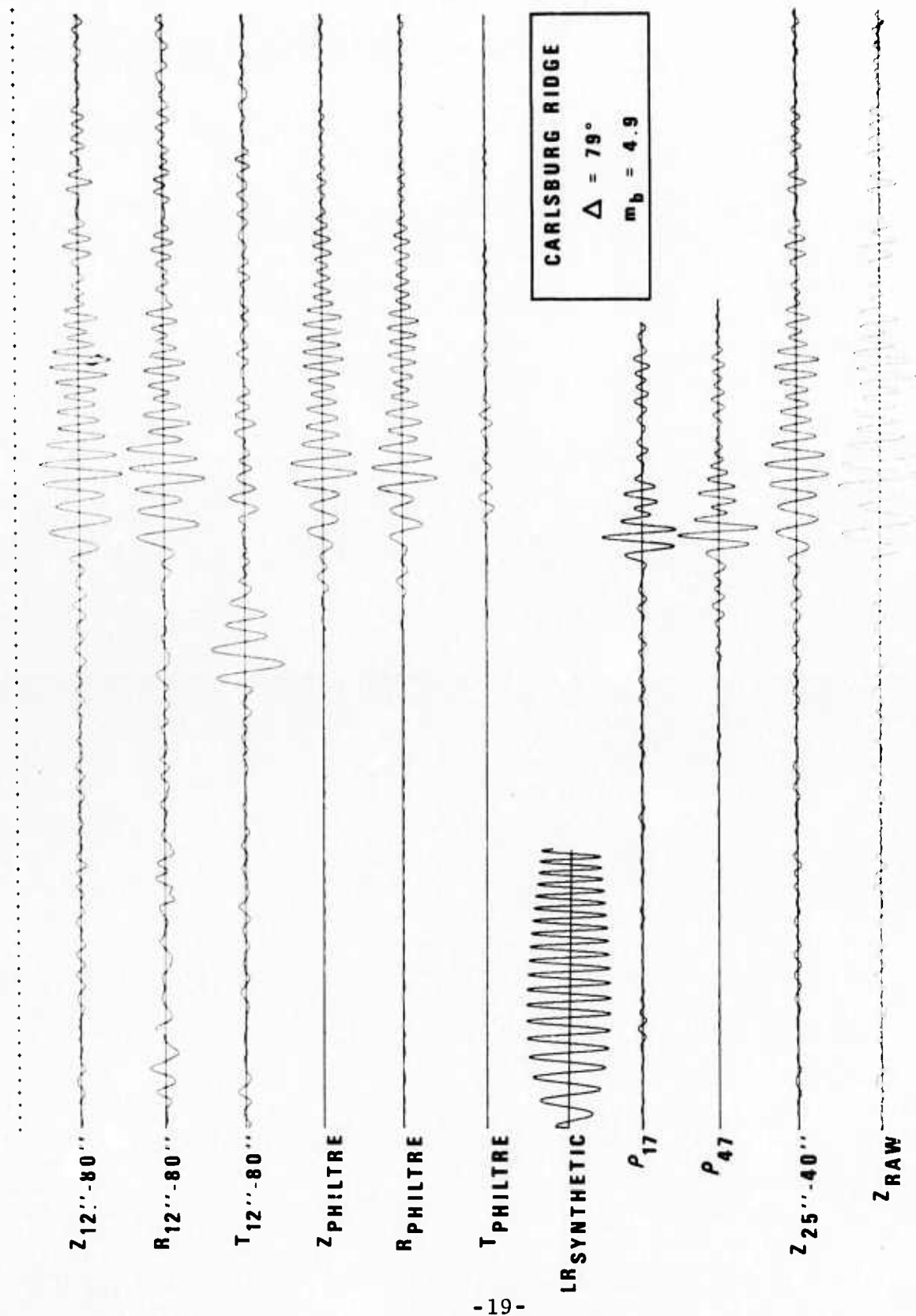


Figure 4. Processing Results for CTA-1

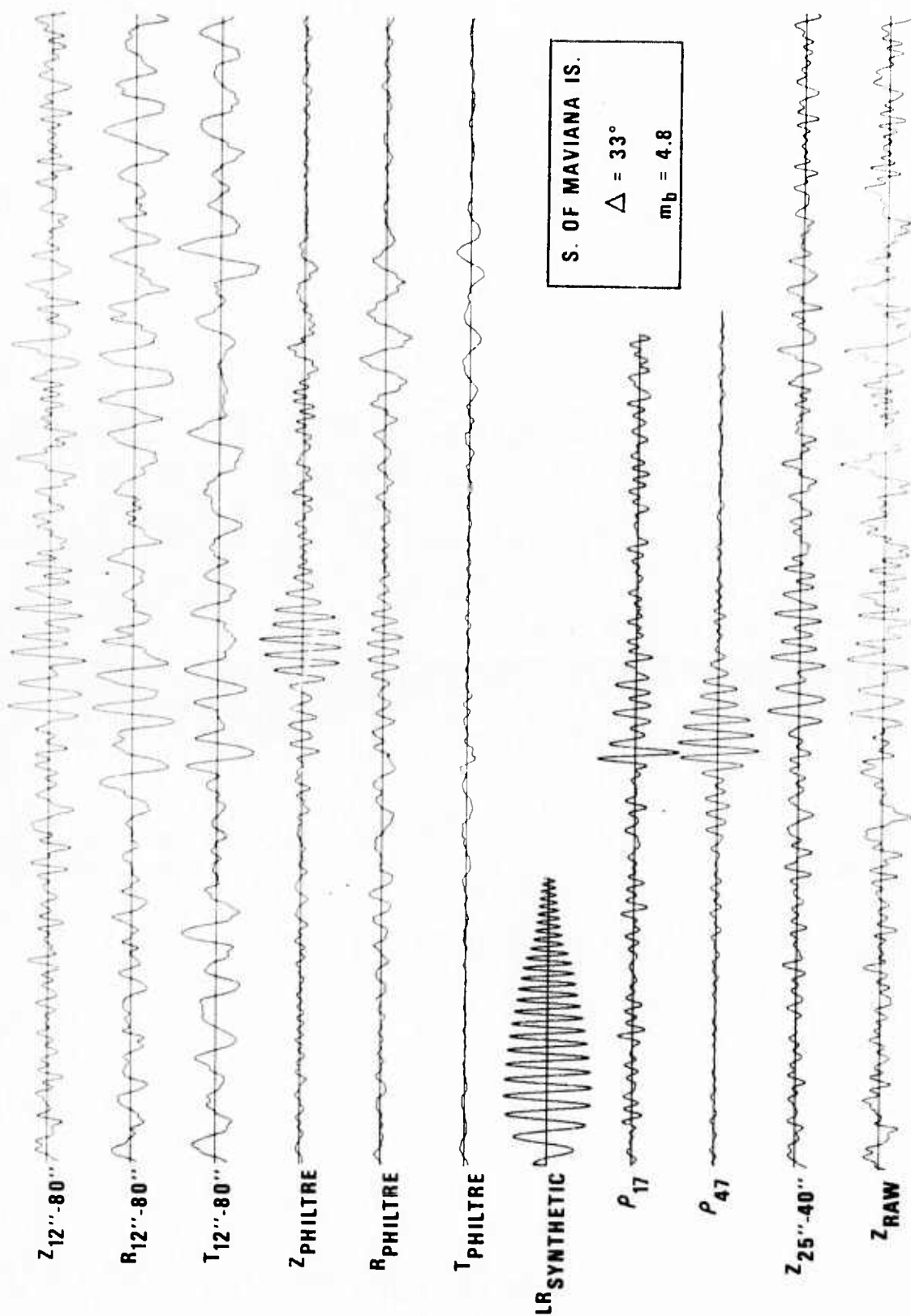


Figure 5. Processing Results for CTA-2

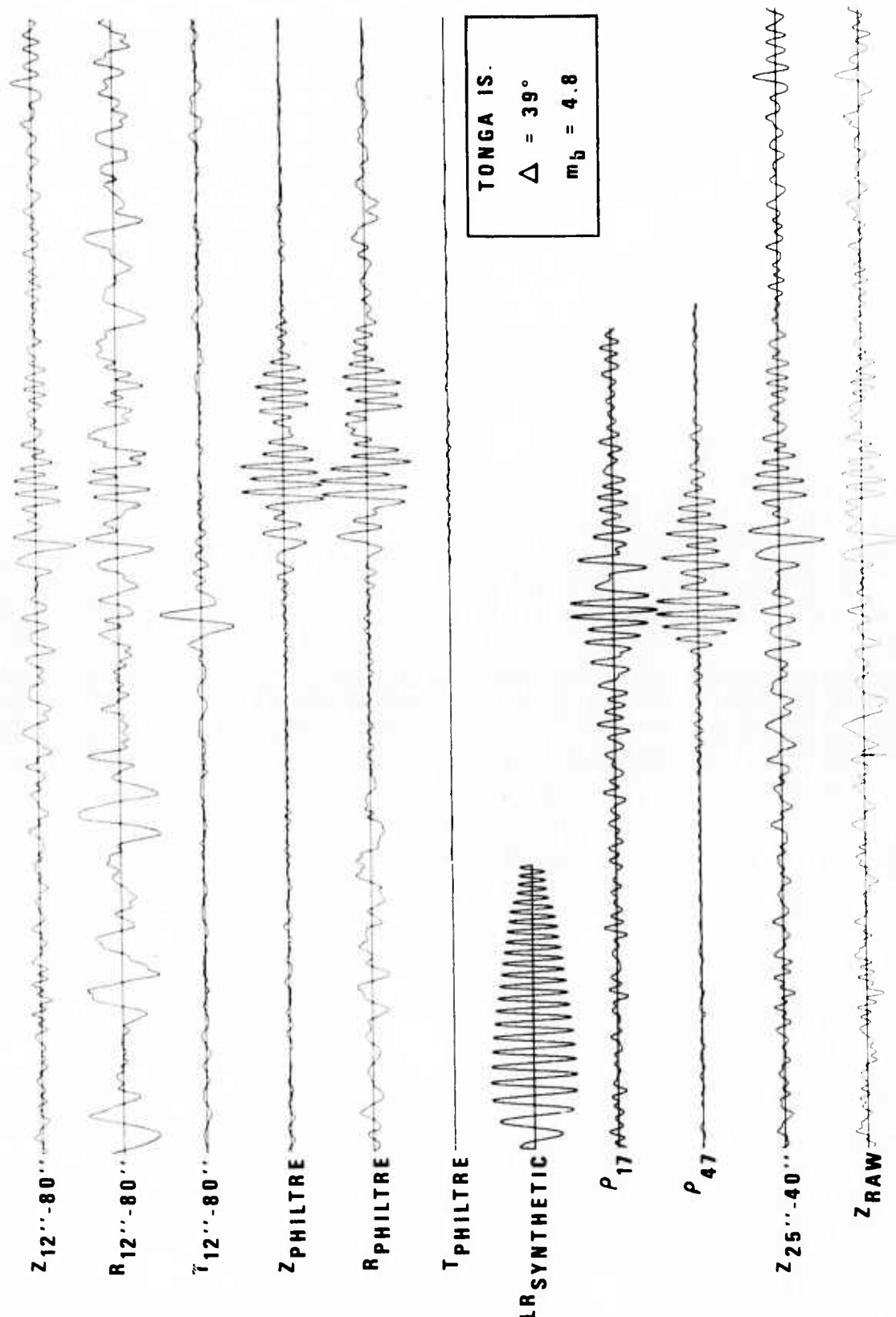


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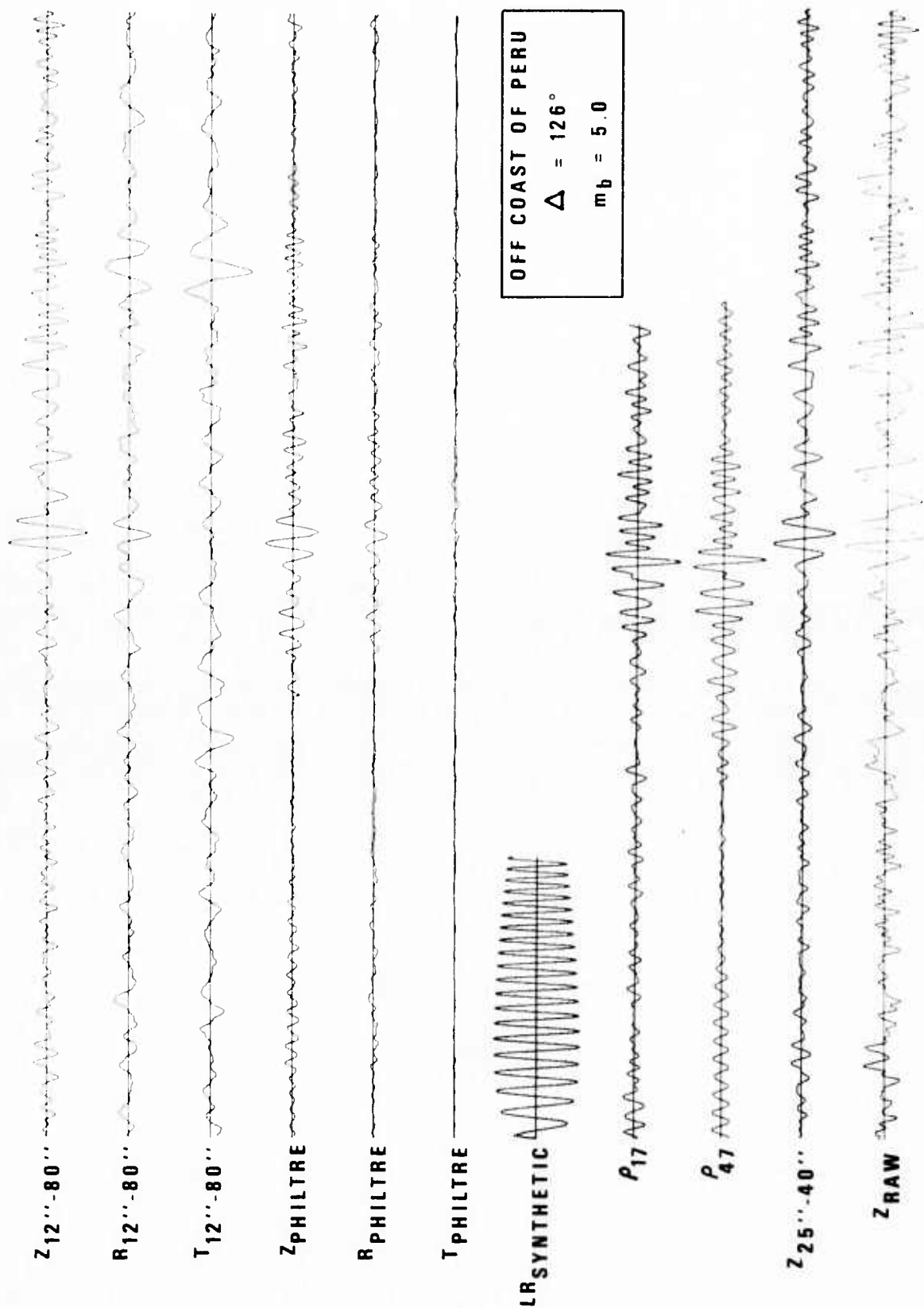
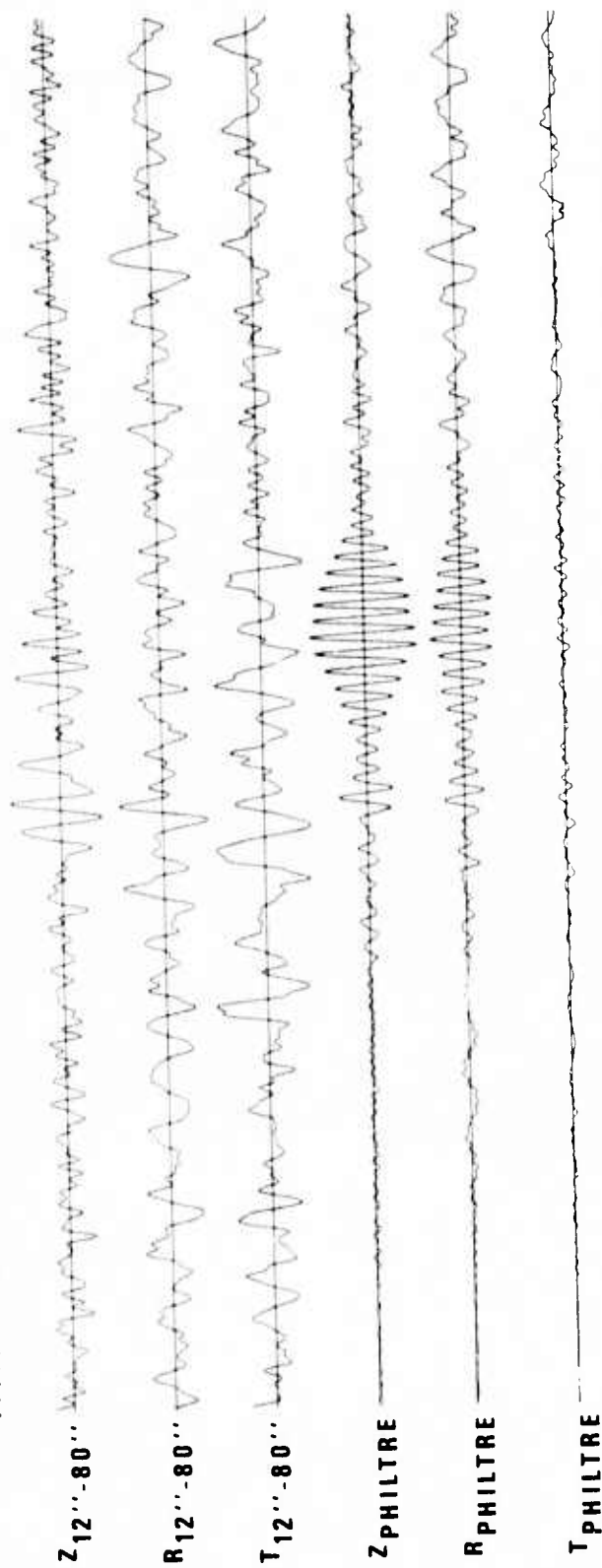


Figure 7. Processing Results for CTA-4



PERU
 $\Delta = 129^\circ$
 $m_b = 4.9$

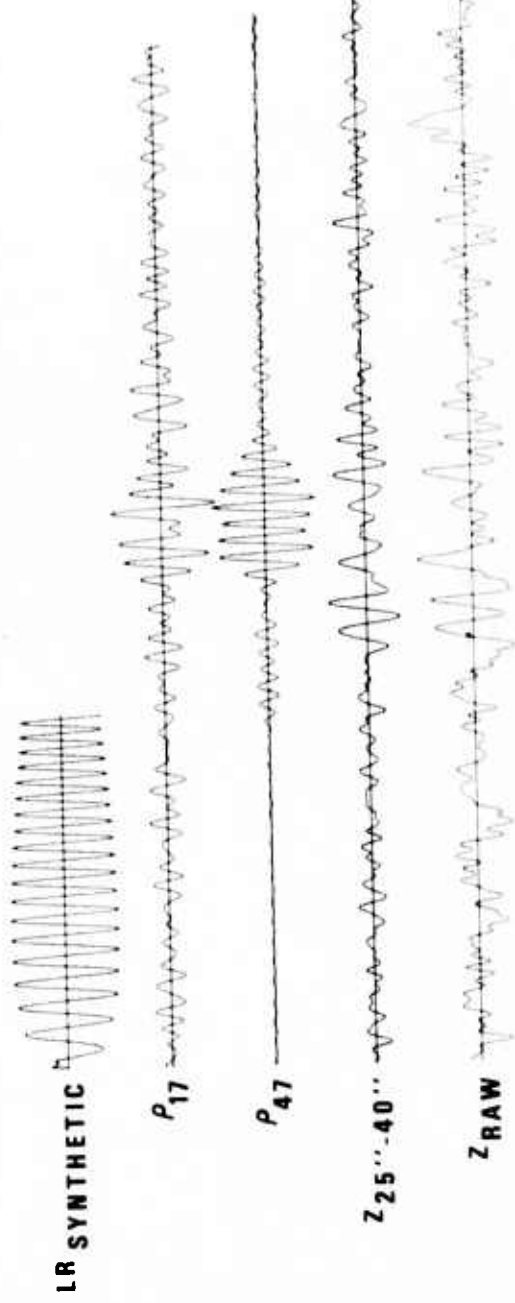


Figure 8. Processing Results for CTA-5

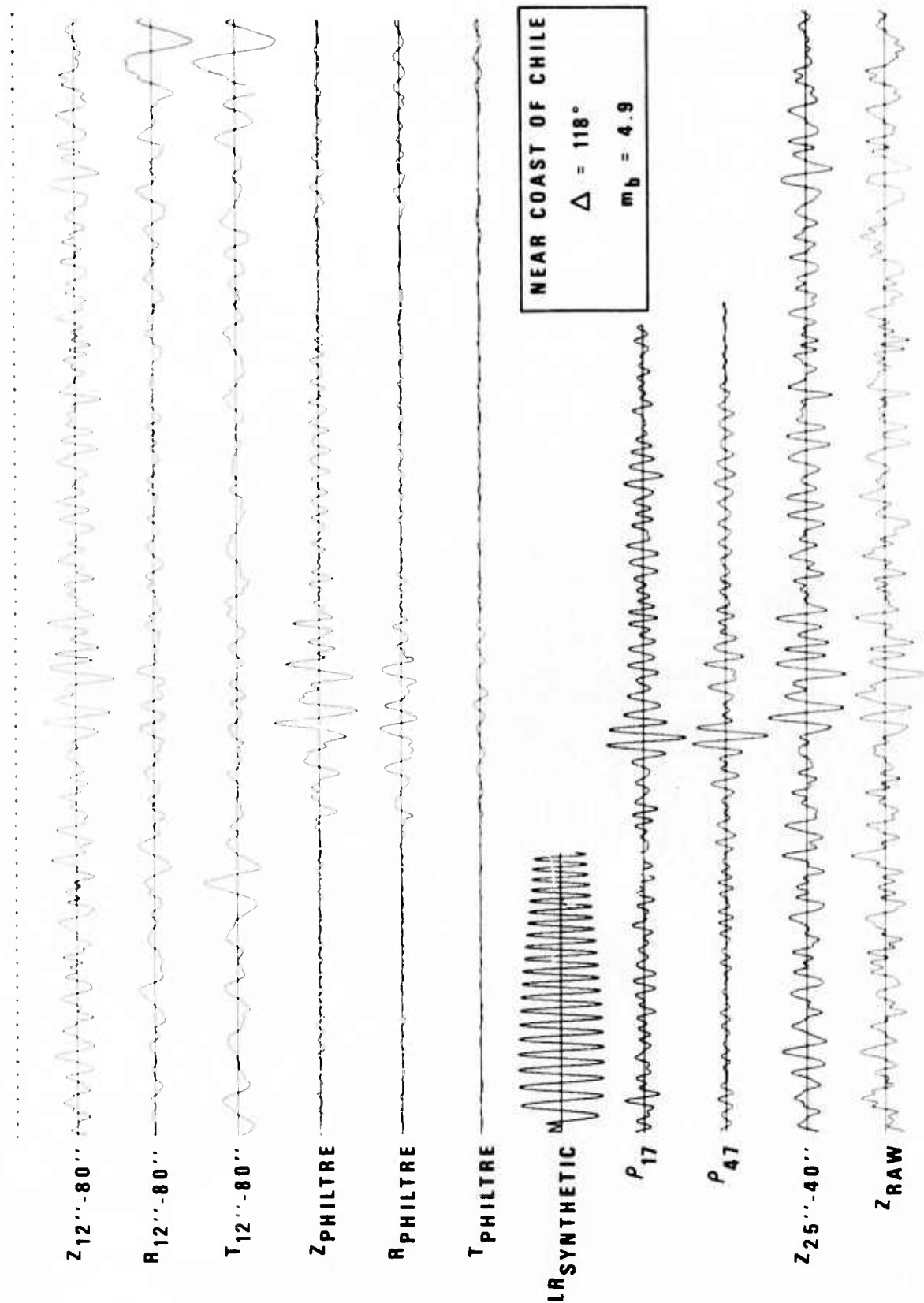


Figure 9. Processing Results for CTA-6

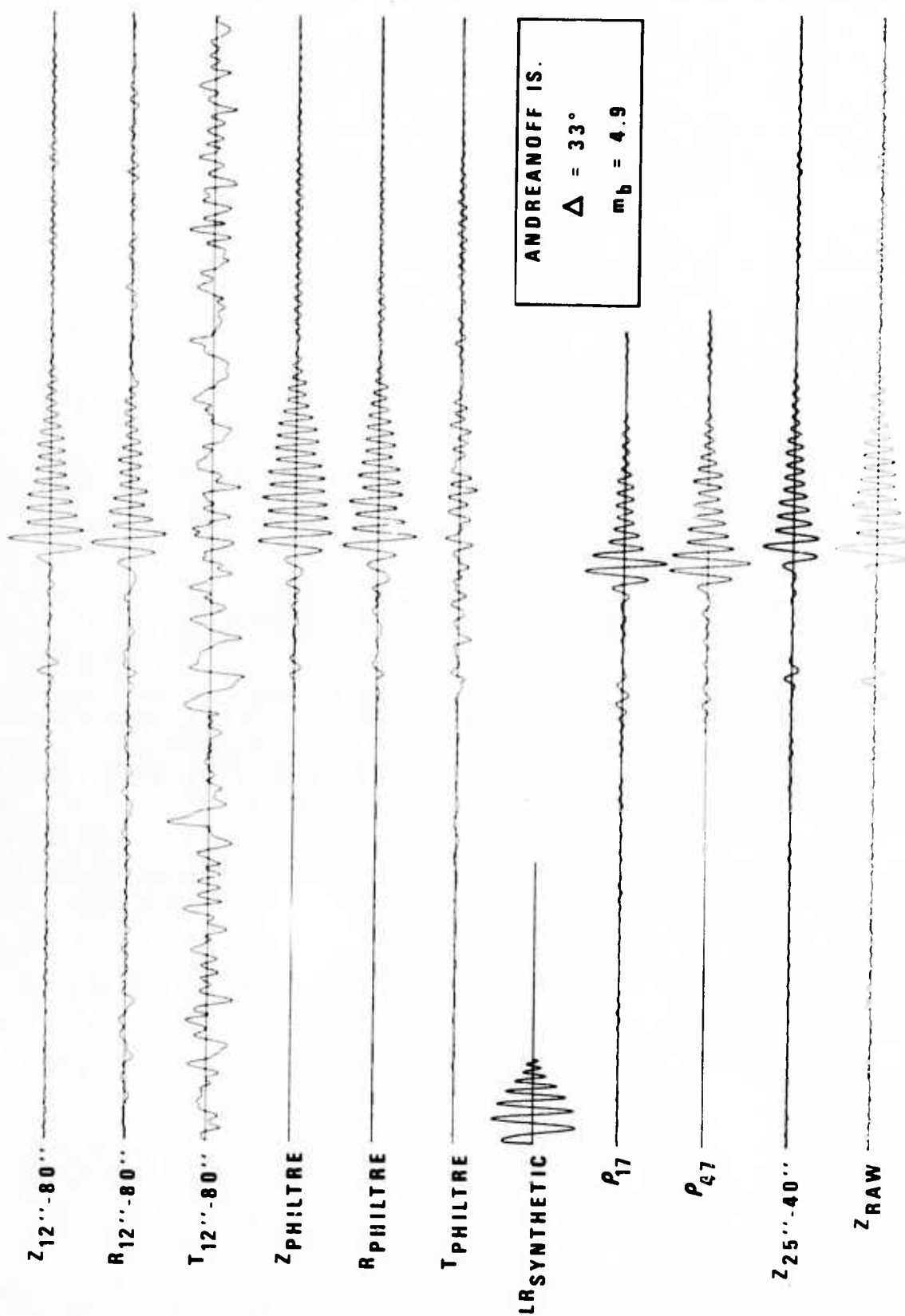


Figure 10. Processing Results for KIP-1

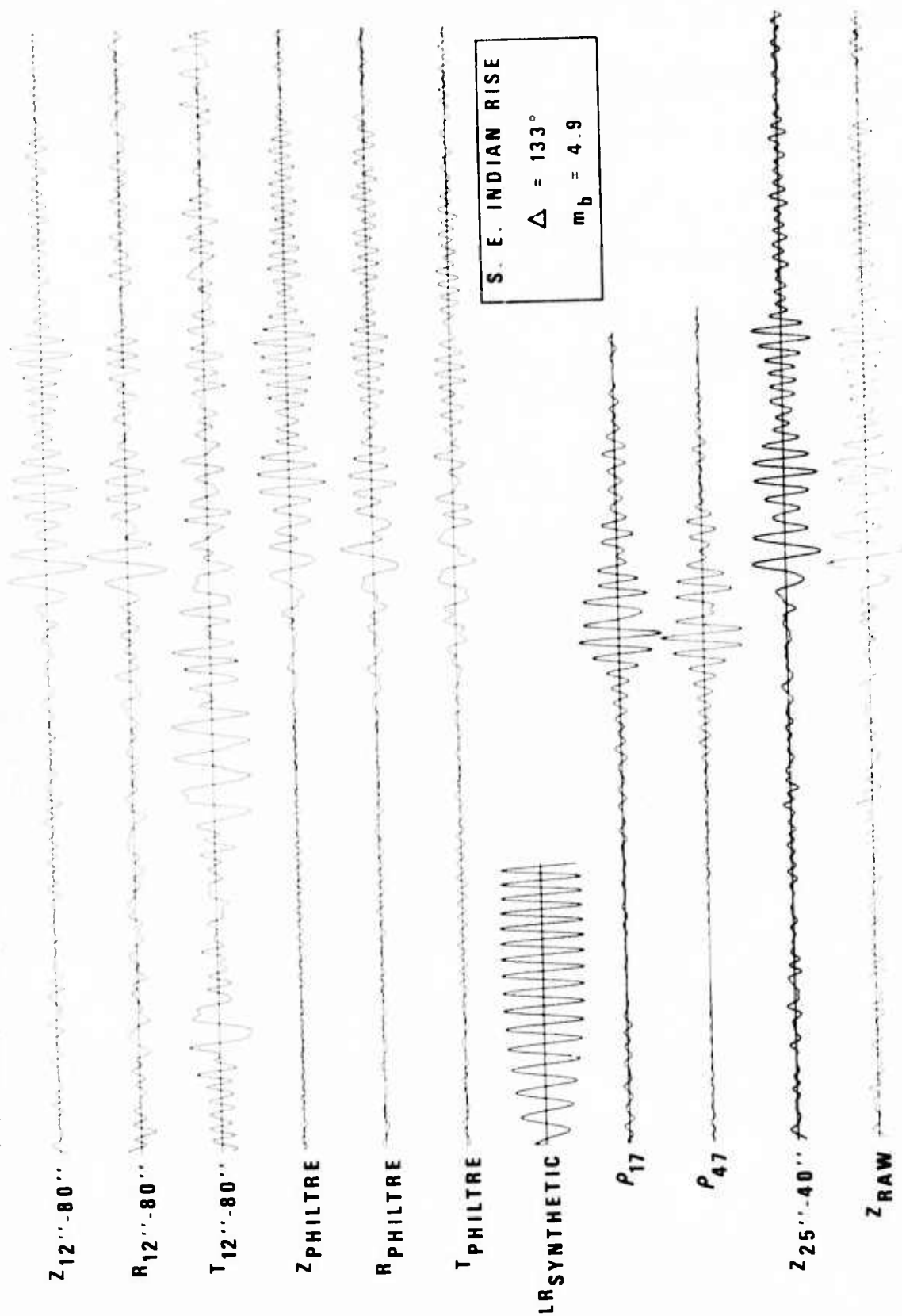


Figure 11. Processing Results for KIP-2

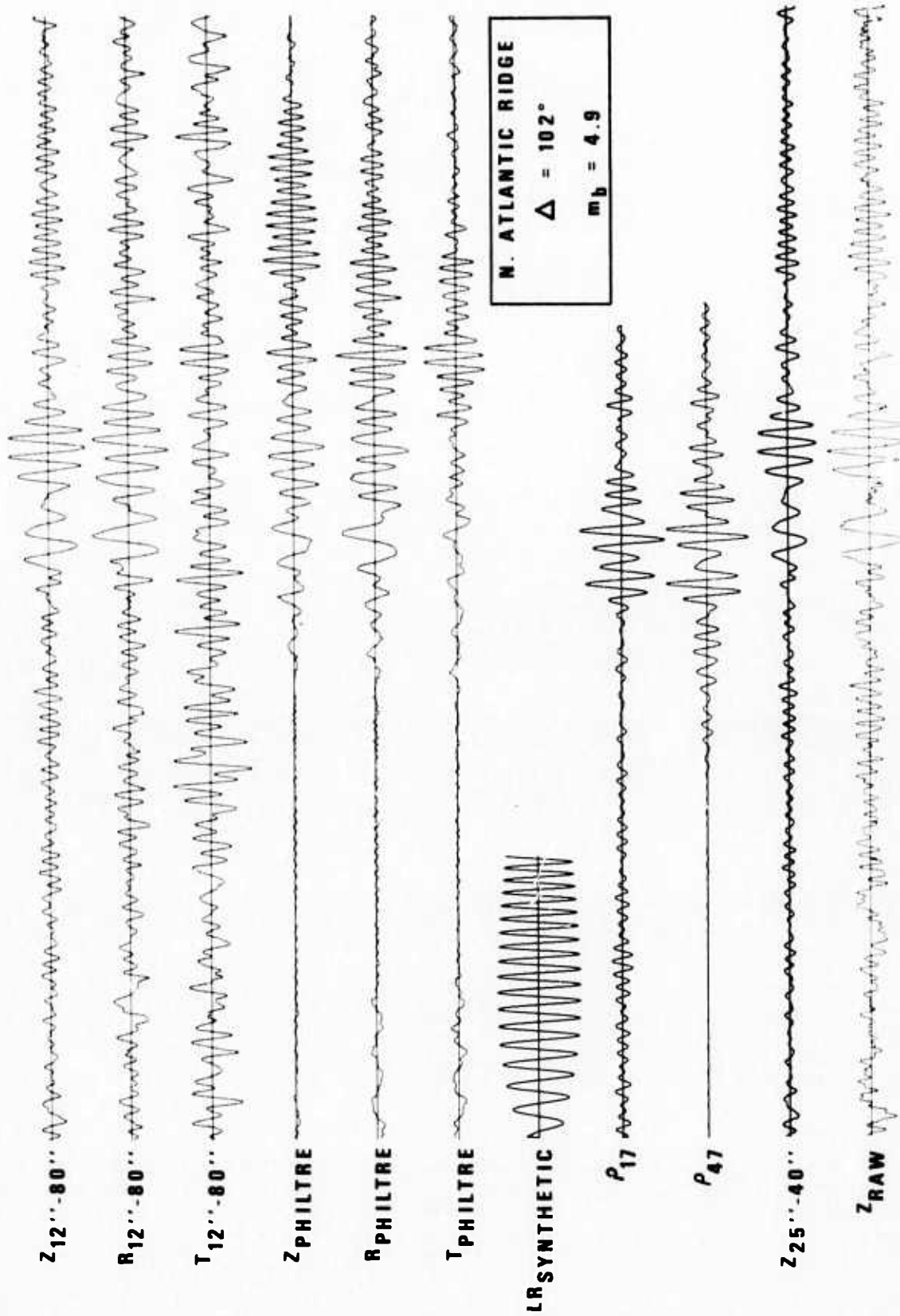


Figure 12. Processing Results for KIP-3

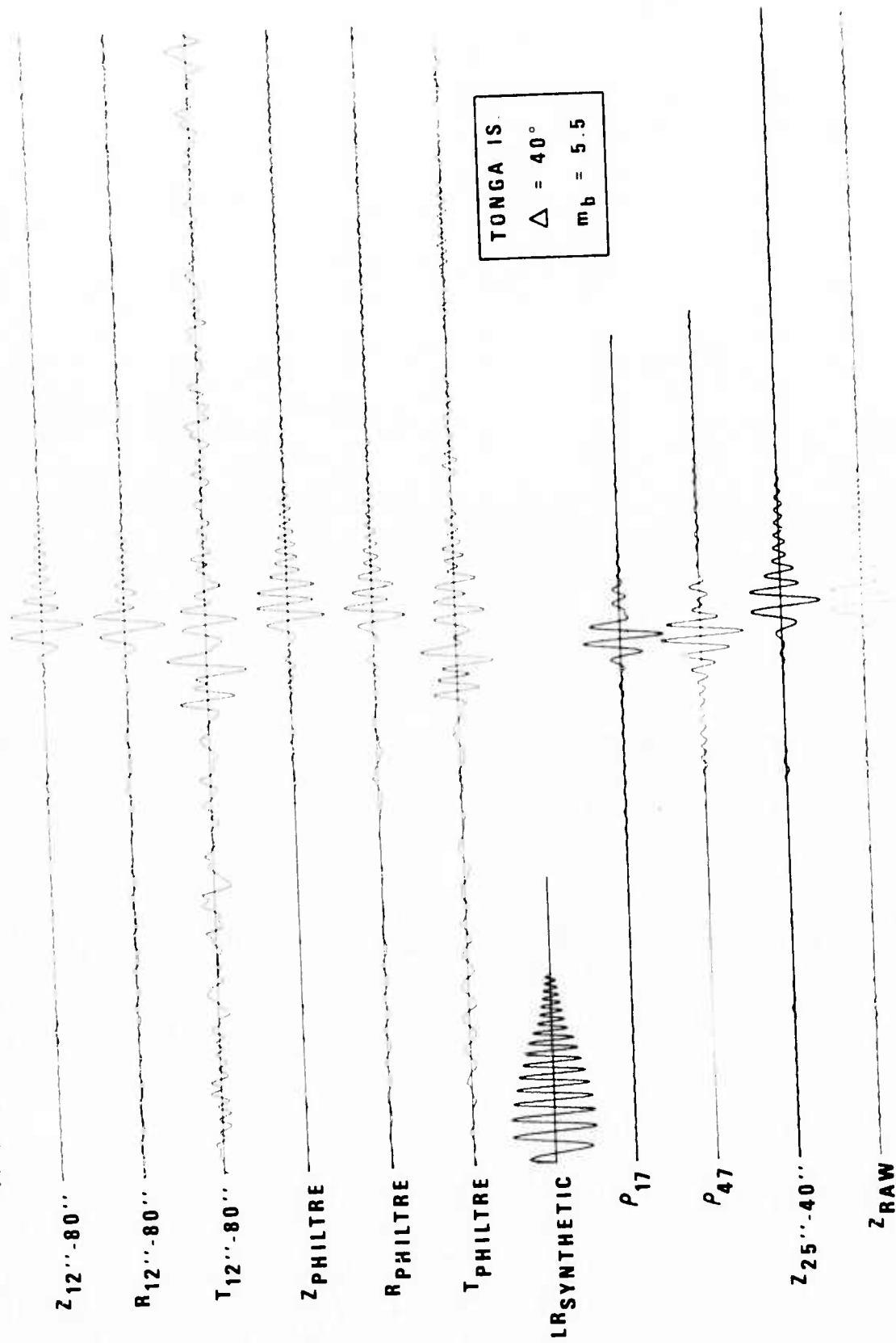


Figure 13. Processing Results for KIP-4

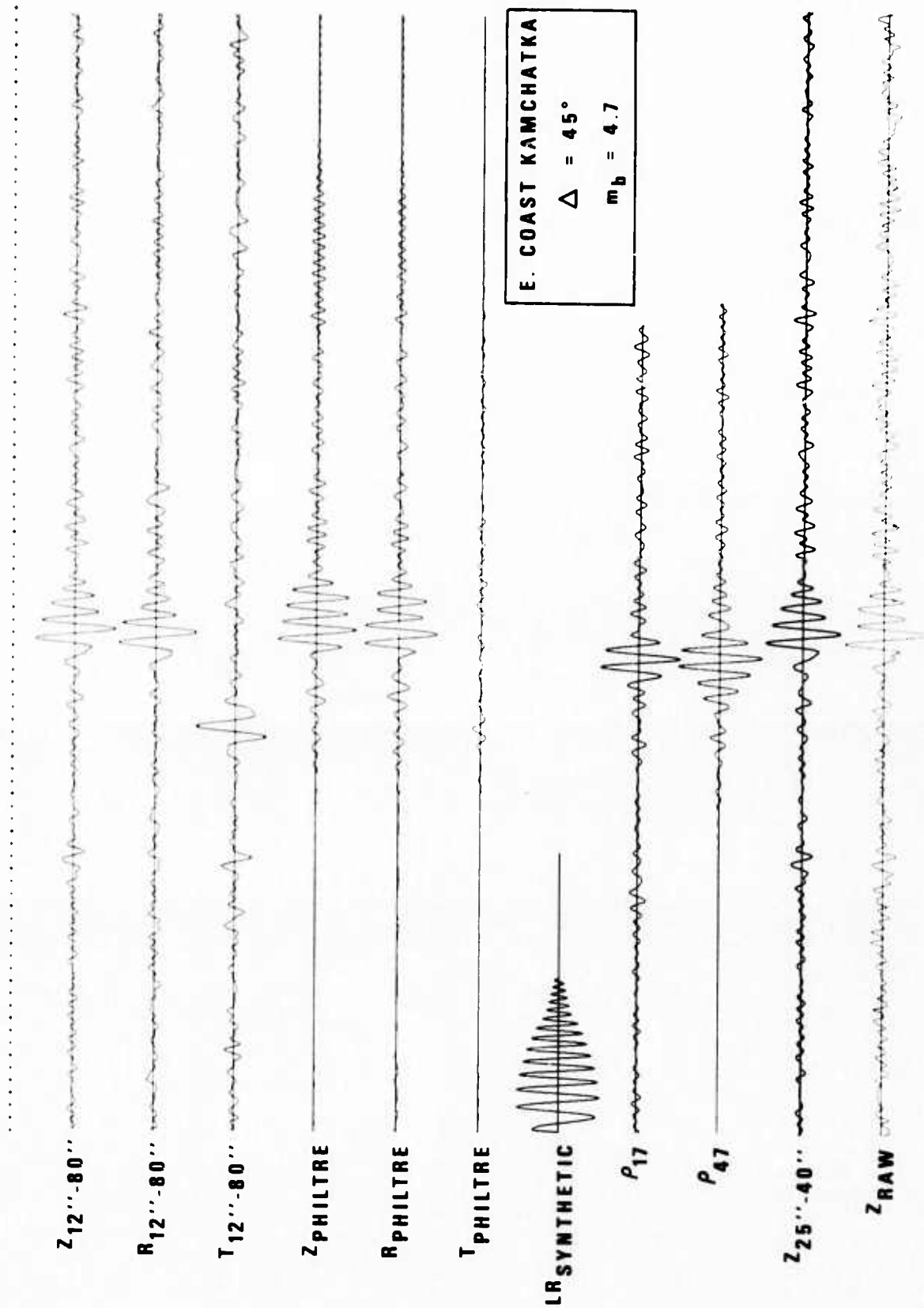


Figure 14. Processing Results for KIP-5

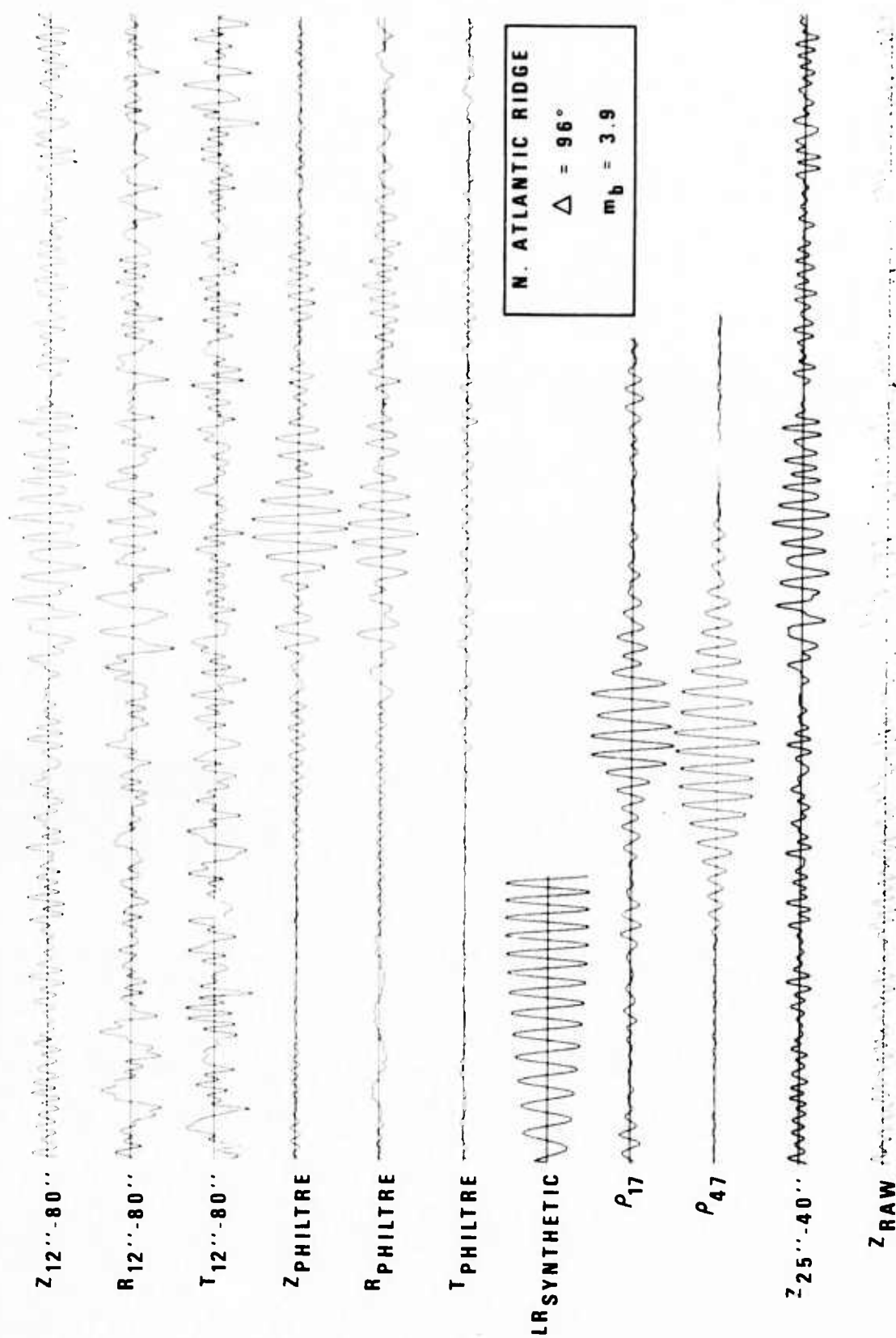


Figure 15. Processing Results for KIP-6

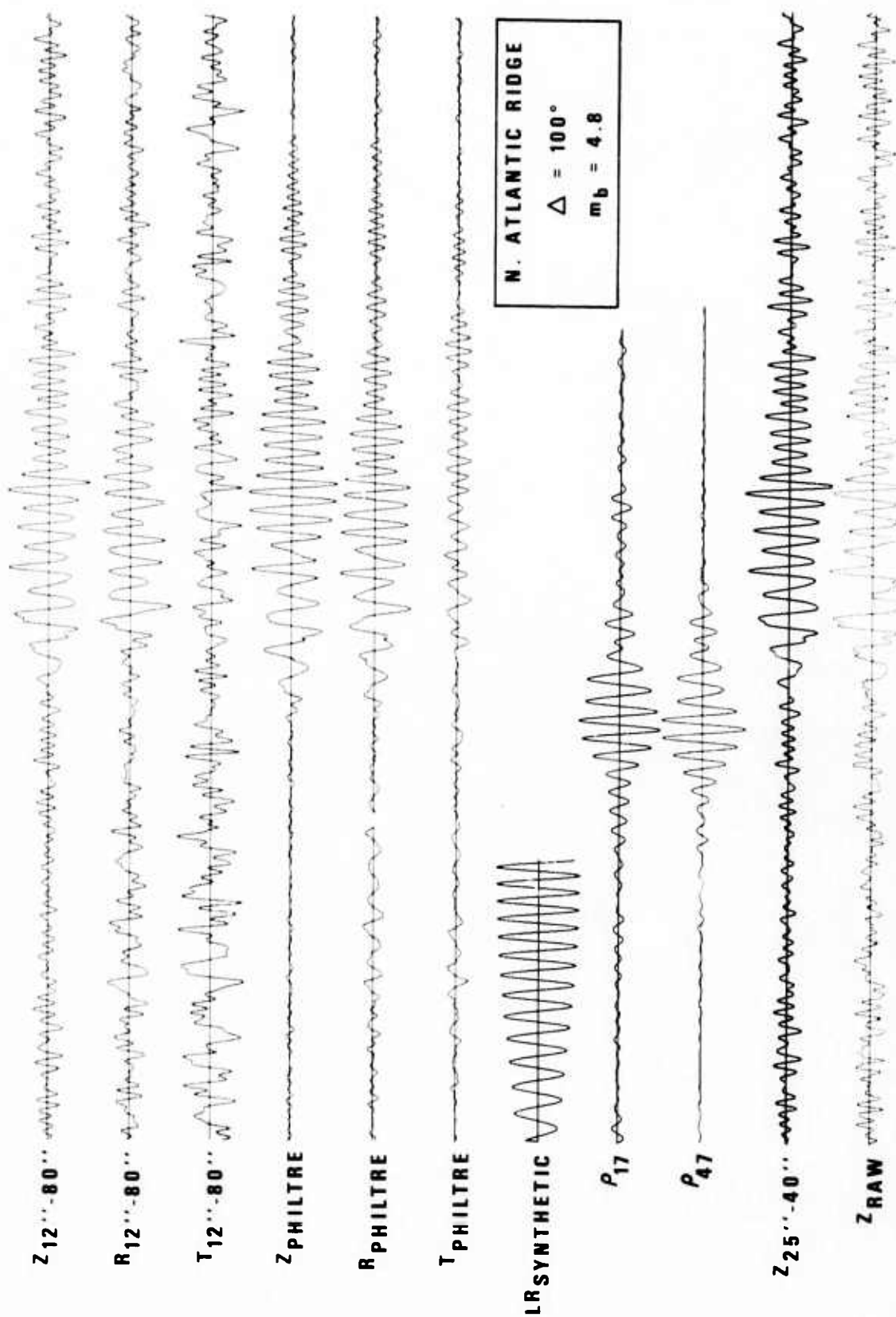


Figure 16. Processing Results for KIP-7

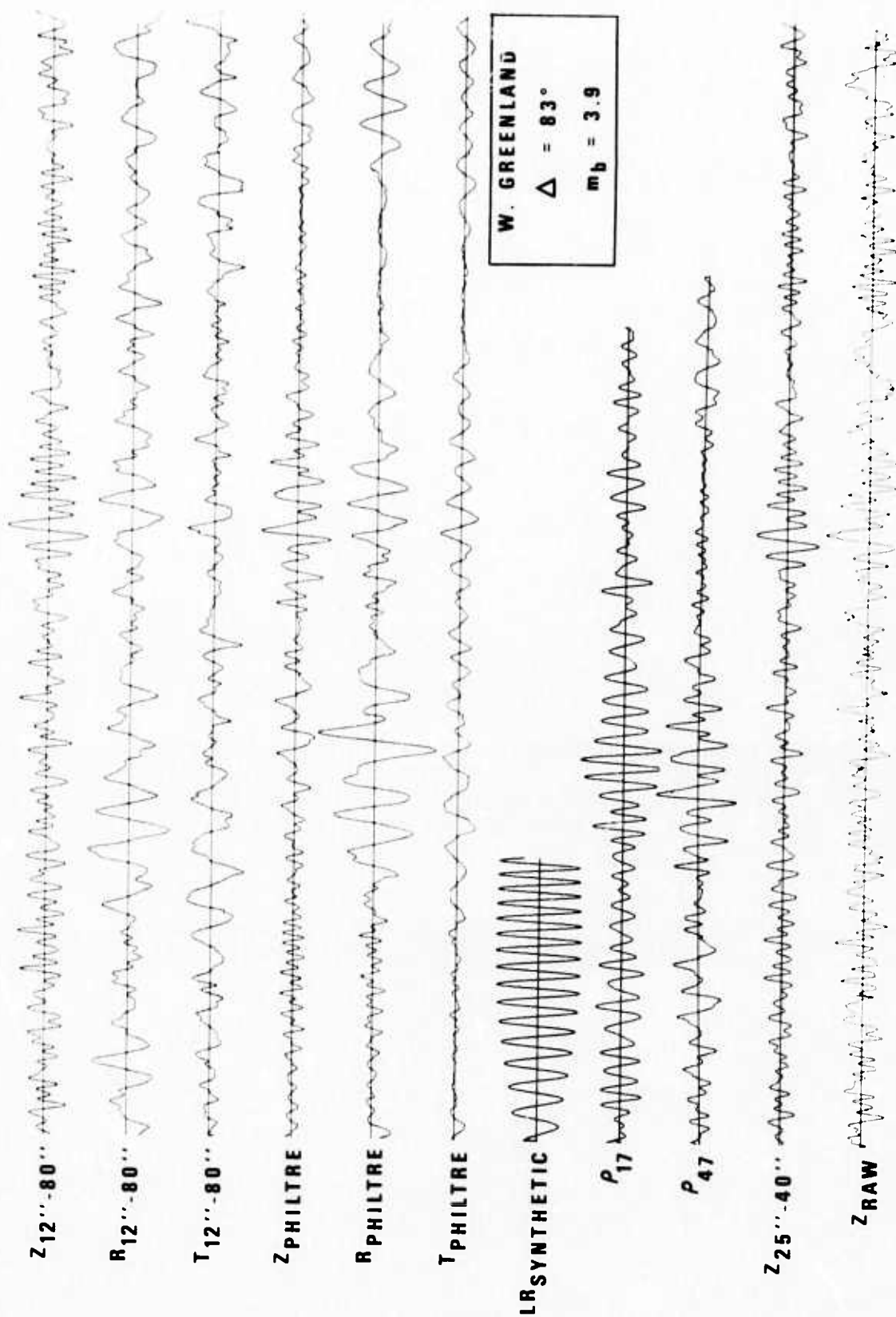


Figure 17. Processing Results for KIP-8

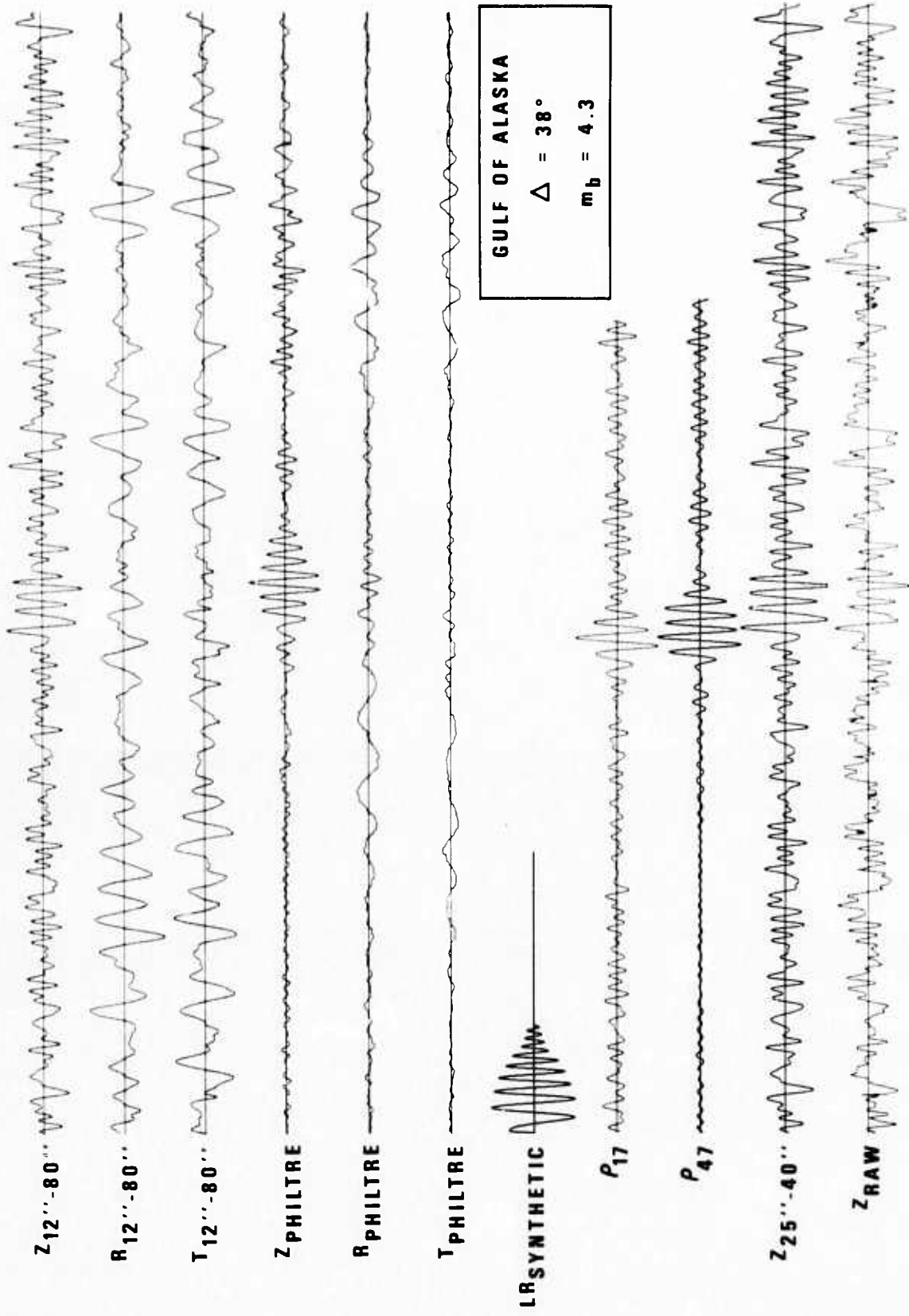


Figure 18. Processing Results for KIP-9

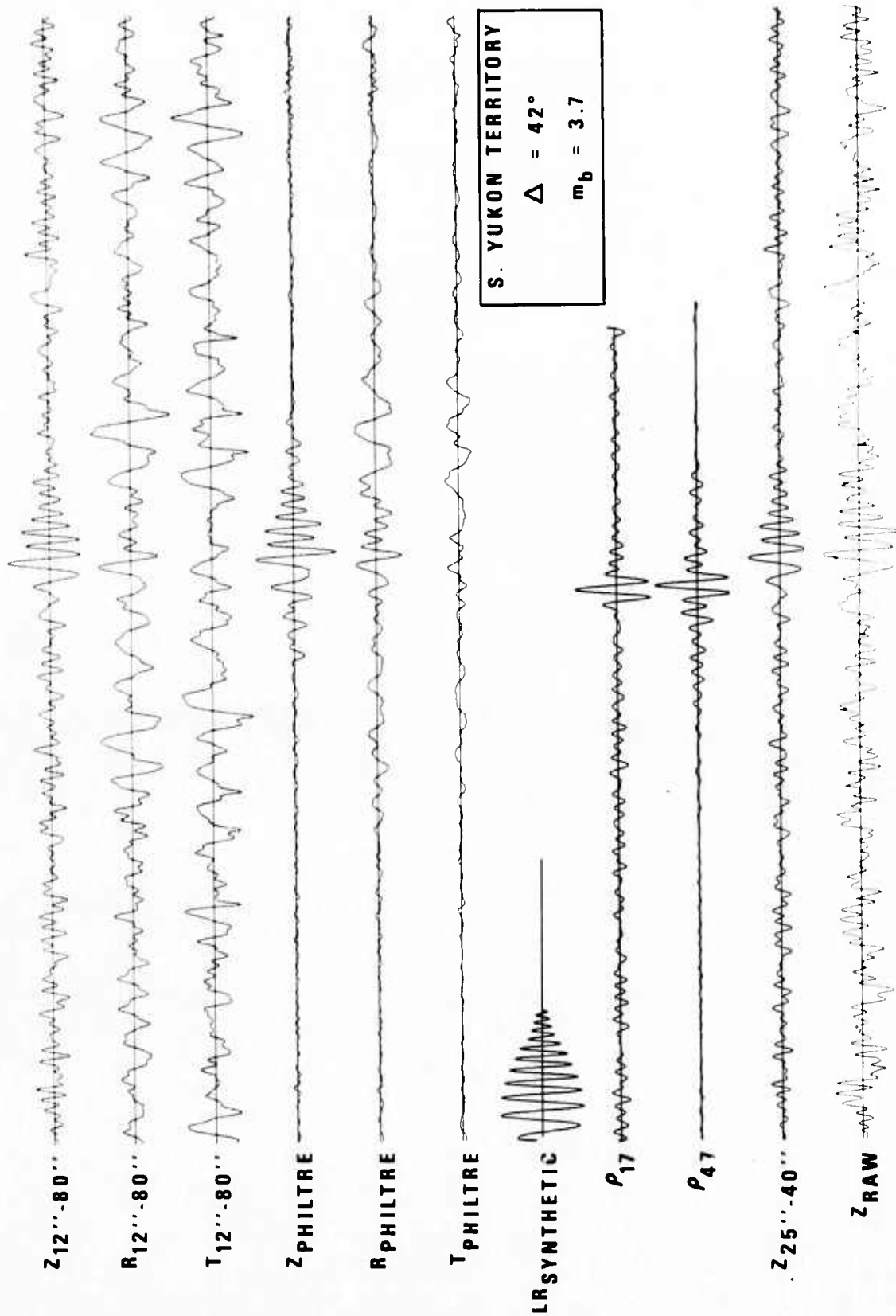


Figure 19. Processing Results for KIP-10

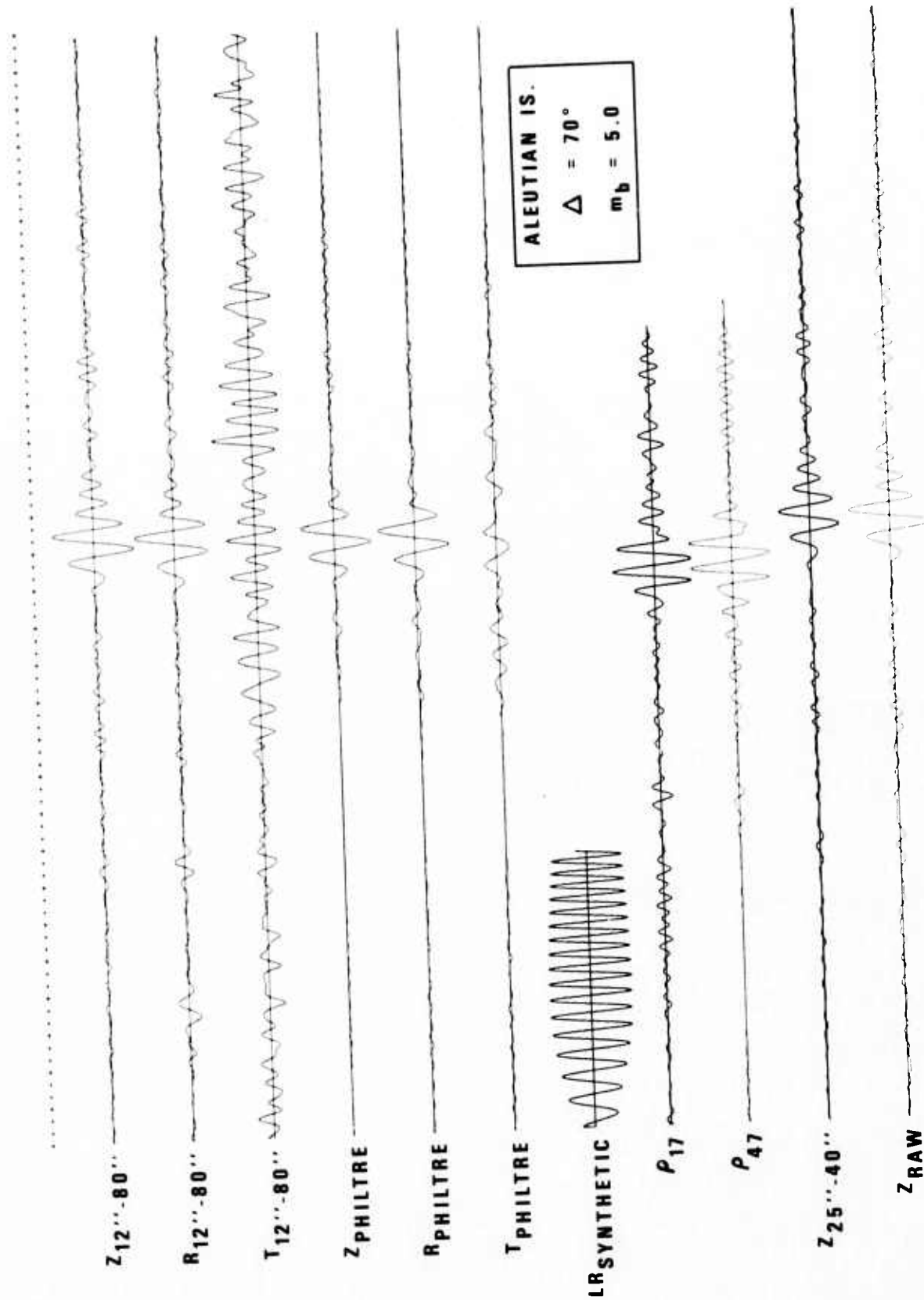


Figure 20. Processing Results for KON-1

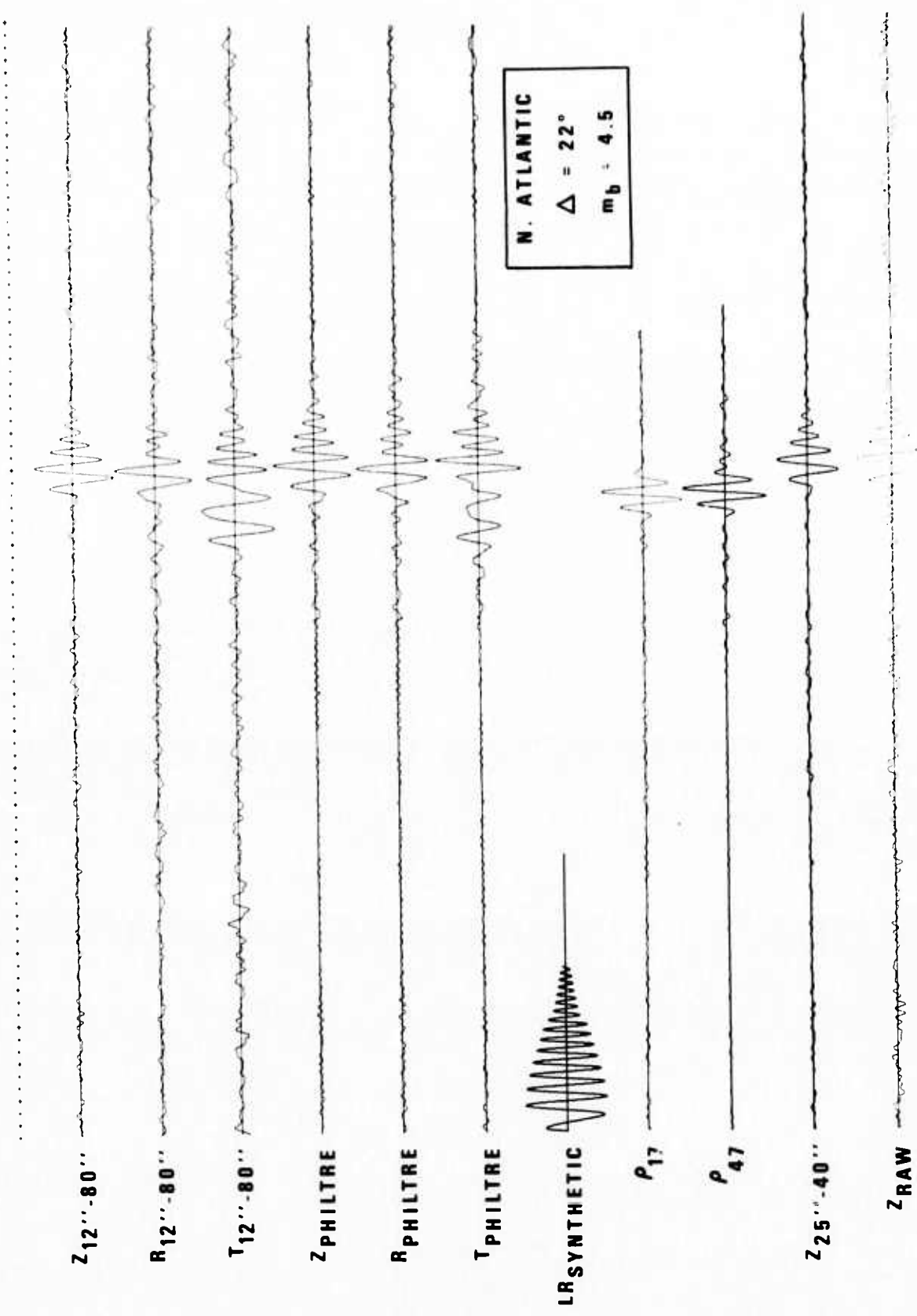


Figure 21. Processing Results for KON-2

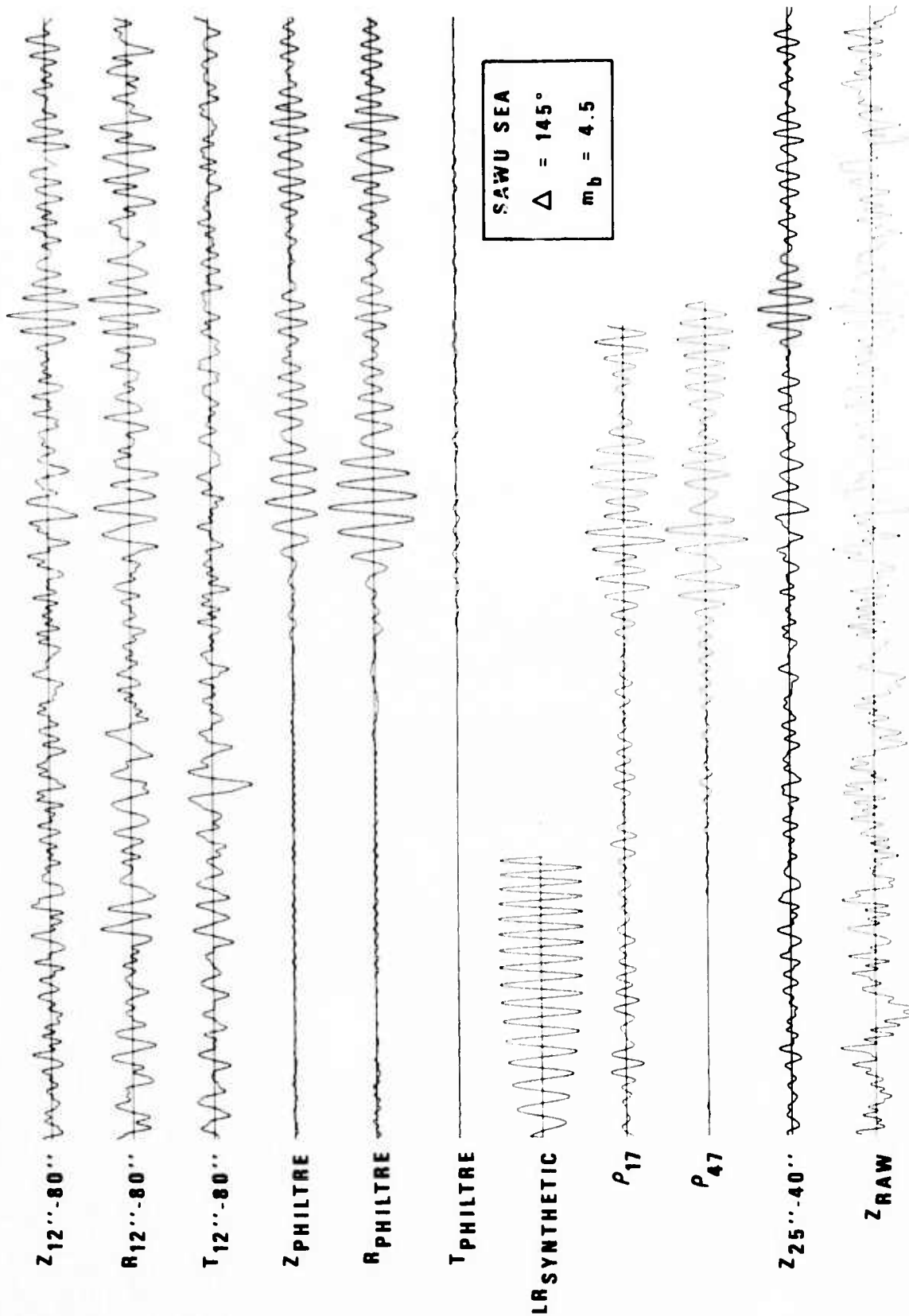
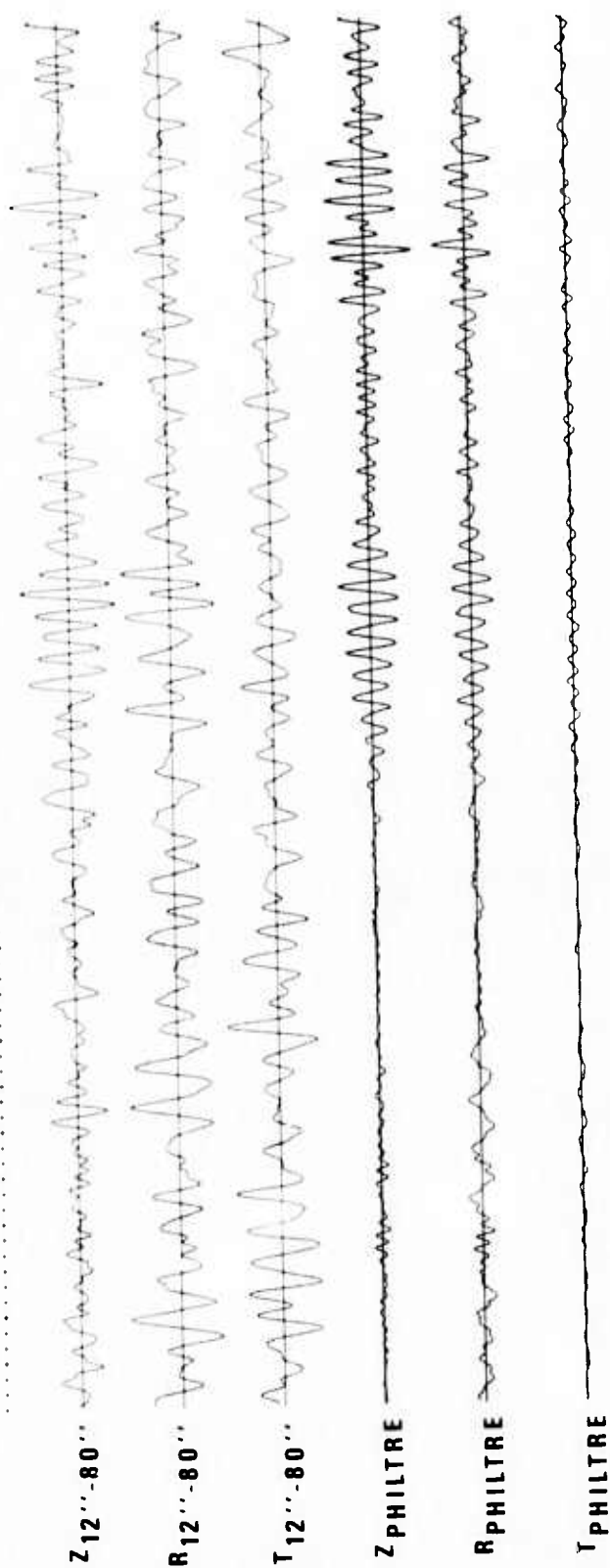


Figure 22. Processing Results for KON-3



E. COAST KAMCHATKA
 $\Delta = 62^\circ$
 $m_b = 4.3$



LR SYNTHETIC

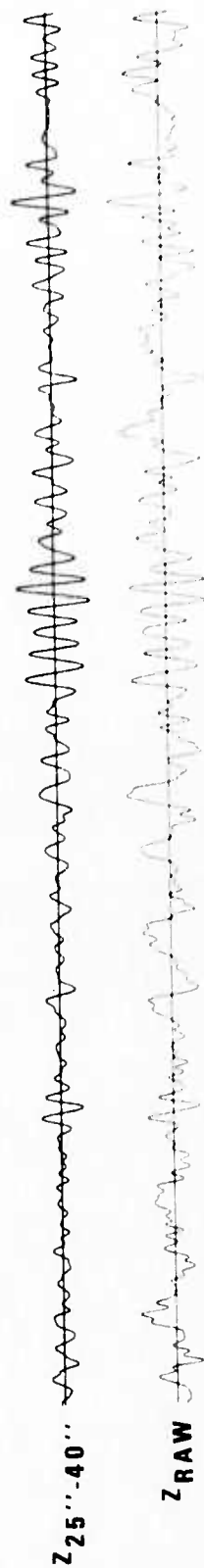
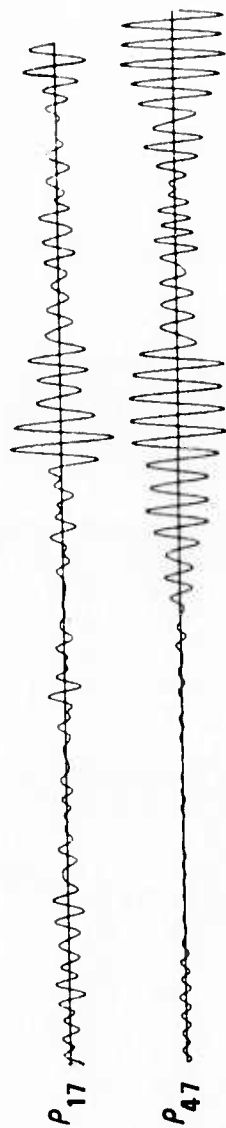


Figure 23. Processing Results for KON-4

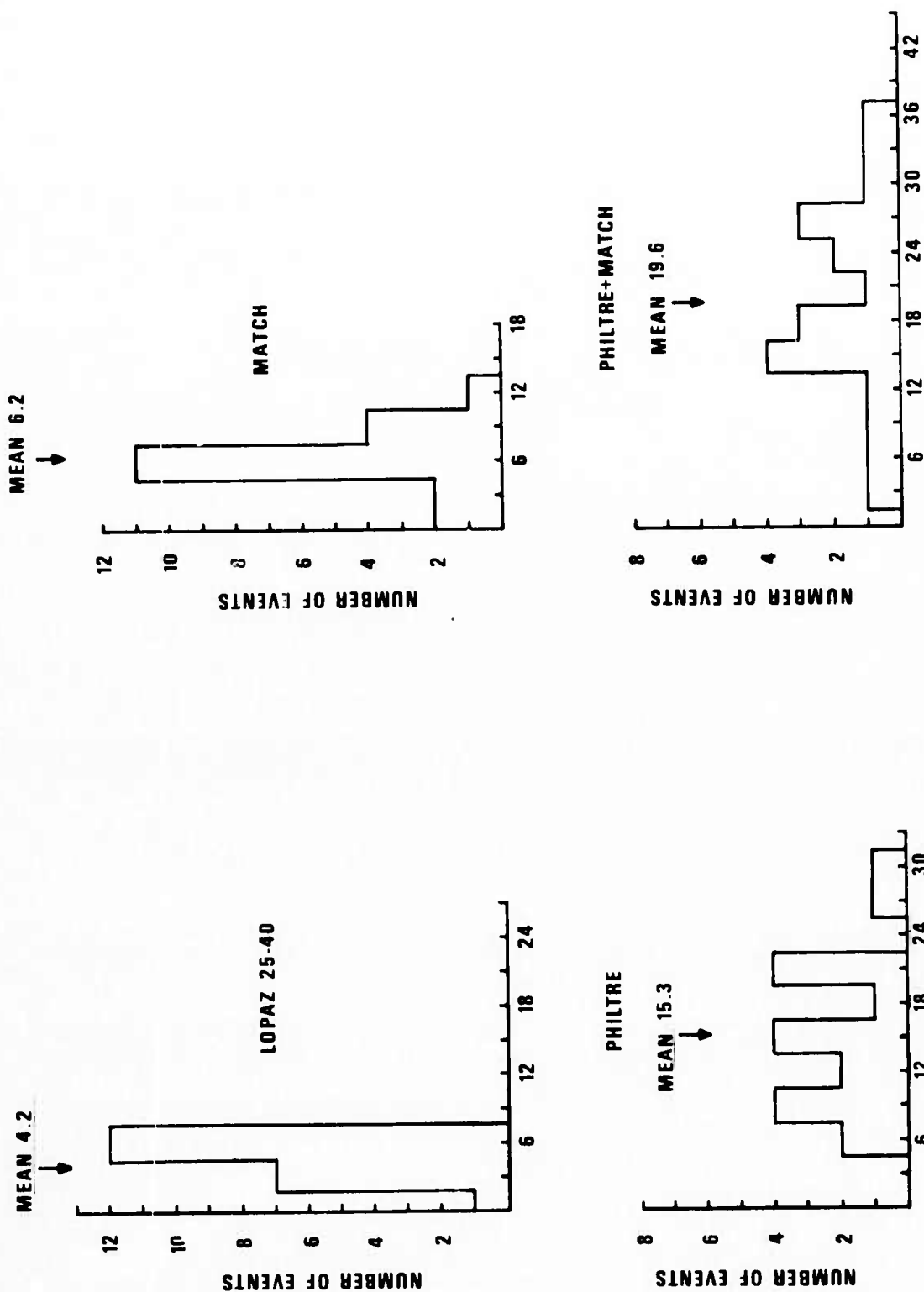


Figure 24. Histograms of signal enhancement by each of the four processors on 25 events

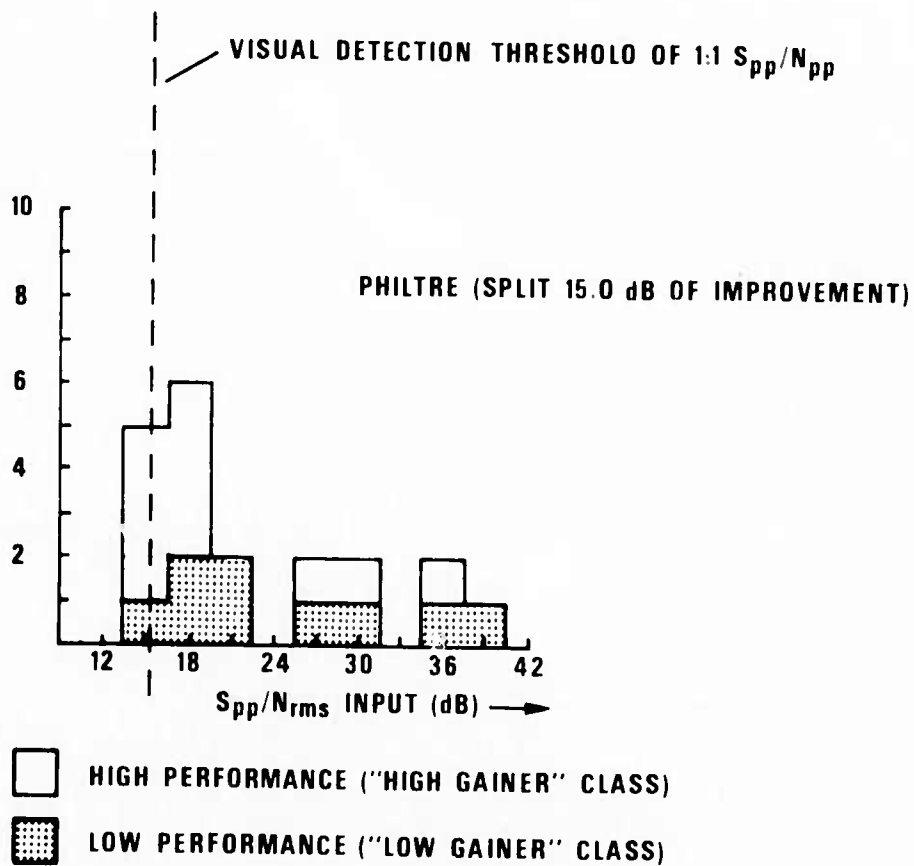
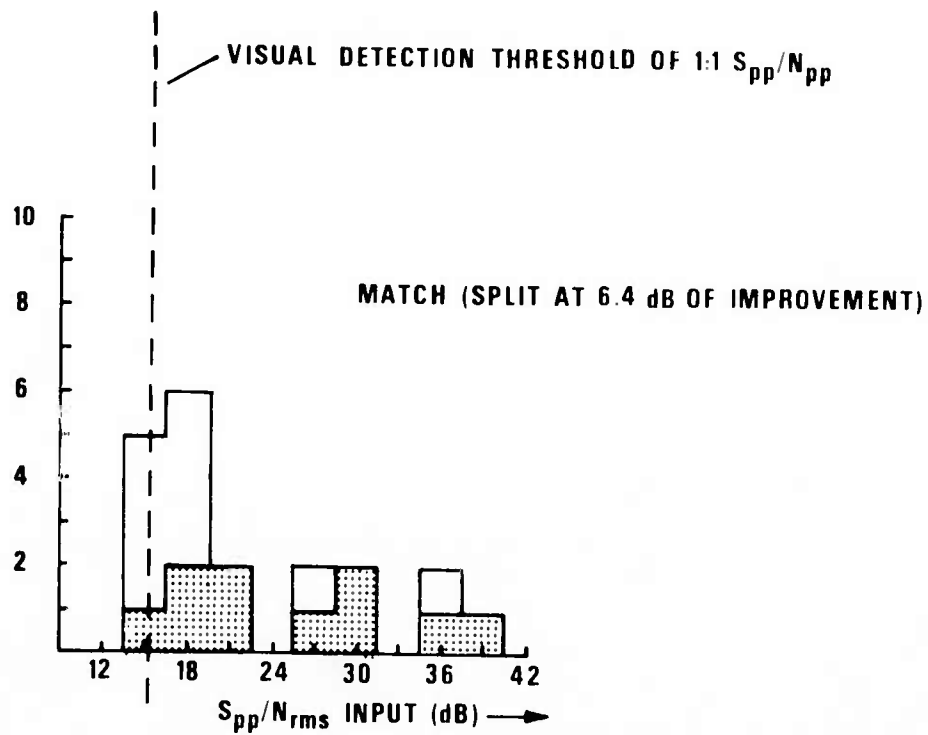


Figure 25. Distribution of raw signal/noise ratios